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Hydrology, Erosion, and Water-Quality Studies in the Southern Great Plains Research Watershed, Southwestern Oklahoma, 1961-78

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Hydrology, Erosion, and Water-Quality Studies in the Southern Great Plains Research Watershed, Southwestern Oklahoma, 1961-78

Prepared by Staff,
Water Quality and Watershed Research Laboratory
Agricultural Research Service
Chickasha, Oklahoma

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ABSTRACT

About 18 years of research data were collected to determine the hydrologic effects of the U.S. Soil Conservation Service's conservation and flood-protection program involving construction of flood-retarding structures in a reach of the Washita River totaling 1,130 square miles in southwestern Oklahoma. This report discusses and summarizes data collected on watershed physical characteristics, precipitation and climate, soil moisture and infiltration, remote sensing of hydrologic parameters, runoff from unit-source areas and the Washita River and its tributaries, floodwater-retarding structures, ground-water movement and quality, surface-water quality, erosion and sediment yield, sediment transport, channel stability, and hydrologic modeling. Also discussed are the development and testing of water-level measuring devices, the Chickasha sediment sampler, and other equipment that filled the need for certain specialized items of equipment that were not commercially available for use in these studies. Index terms: hydrologic modeling, hydrology, Oklahoma, SCS floodwater-retarding structures, sediment yield and transport, soil moisture and infiltration, Washita River basin, water quality, watershed precipitation and climate.

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Section 1.—Introduction

Man has become aware that his occupancy, use, and modification of a river basin may cause changes in the river. Conservation programs in the uplands of the basin and on the tributaries are among the activities that could affect the river. One of the first concerns with river performance is the total volume of flow available for use. Will this quantity be diminished by conservation practices applied to the watershed, or will the flow be made more steady and the supply more reliable by these activities? Another vital concern is the effect of the conservation programs on floods. To what extent will the upstream flood-control program diminish the major floods on the main stem? Other questions also need to be answered. Can the flood plain be utilized more intensively? What is the effect of these conservation activities on the quality of the water in the stream? Will the sediment flow be reduced by erosion-control activities, resulting in a clearer stream and better water? Would a reduction in the amount of sediment produced by the basin or a change in the character of the sediment delivered to the river affect the river itself? Since a river shapes itself to carry the water and sediment it receives with the least amount of work, it is reasonable to expect a change in the river if the input of water and sediment is changed.

The Washita River has a long history of devastating floods causing millions of dollars of damage and loss of life and property. Therefore, the Department of Agriculture was authorized by the Congressional Flood Control Act of 1944 to undertake works of improvement in the Washita River basin (fig. 1-1) for floodwater-retardation and soil-erosion control. The work included floodwater-retarding structures, drop inlet structures, floodwater diversions, channel improvements, and floodways. The Soil Conservation Service began the construction in 1946.

Floodwater-retarding structures generally have a drainage area of less than 5 square miles and are designed with principal spillways having capaci-

ties of 10 to 15 cubic feet per second per square mile to provide controlled release for floods up to the 25- to 100-year frequency range. Protection of agricultural land is provided by storage between the principal and emergency spillways. Storage for either 50- or 100-year sediment accumulation is provided below the principal-spillway elevation. Most of a watershed must be treated with recommended conservation practices for reduction of erosion and sediment transport to qualify for installation of floodwater-retarding structures.

The Southern Great Plains Research Watershed was established in 1961, with headquarters at Chickasha, Okla. (fig. 1-1). The project was recommended in U.S. Senate Document 59 in 1959. The following paragraphs from that document state the purpose and need for the project:

This region is seriously ravaged by floods and attendant sedimentation problems. A major research effort should be carried out on the effect of the flood control and water shed protection program presently in an advanced state of development. Such studies would offer the opportunity to gain basic data of direct application to programs of a similar nature that may be applied to other basins. This watershed study would give needed facts directly applicable to the streams and watersheds transecting the break from the plains to the prairies and cross-timbers area. In addition, it would provide much needed information concerning the effectiveness of an applied watershed development program covering features of overall interest to planning technicians throughout the country.

The combination of wide productive flood plains and intense storms has created a serious need for watershed control measures in this region. The overall effects of the applied program should be studied from a hydrologic standpoint for the purpose of improving similar programs of the future.

The Washita River watershed was selected for the studies because the construction of flood-control measures had been started and complete

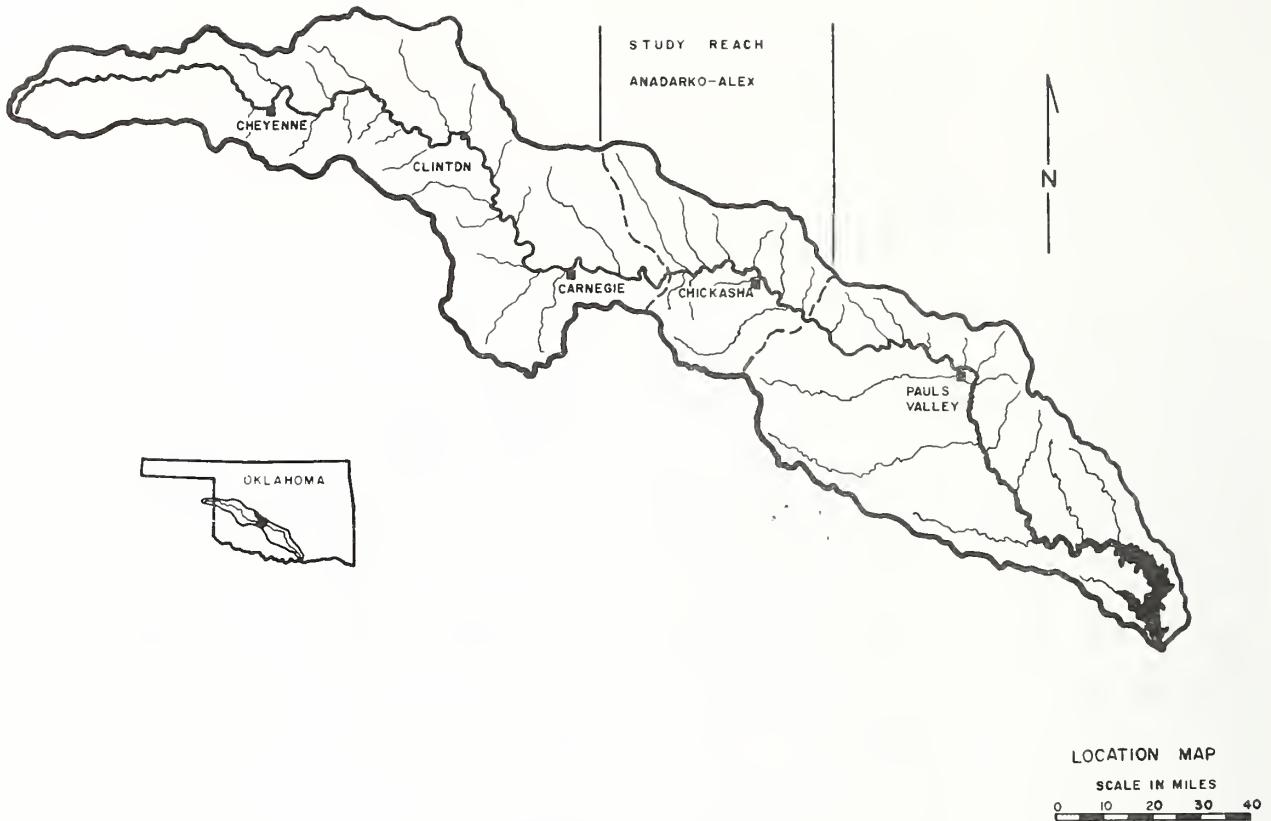


FIGURE 1-1.—Washita River basin.

coverage of the watershed was anticipated. The structures had not been installed in the study reach between Anadarko and Alex, Okla. (fig. 1-1), in 1960. Ideally, several years of hydrologic record could be obtained and then compared with the posttreatment record to determine the hydrologic effects of the treatments. However, within 5 years more than one-third of the study reach had been treated.

Hydrologic data were collected from a recording rain-gage network on a 3-mile grid, 2 climatic stations, about 25 Washita River and tributary runoff stations, sediment-transport

measuring stations, 22 small unit-source watersheds, 8 floodwater-retarding impoundments instrumented for water budgets, and 450 ground-water-level observation wells. Most of the record collection was discontinued in 1978.

The research project has contributed more than 100 publications to hydrologic literature. This report summarizes most of the research findings and conclusions from the study, including the development and testing of hydrologic models. The results of studies outside the Washita River watershed, and some studies not related to the primary research objective, are not included.

Section 2.—Watershed Physical Characteristics

INTRODUCTION

An accurate physical description of a research watershed is necessary to explain the research findings and translate them to other watersheds. The degree to which the findings are applicable to another watershed depends largely on the degree of physical similarity between the watersheds. The natural characteristics of the Washita study reach (fig. 2-1) are described here under the headings of geology, geomorphology, and soils. Works of man that affect the watershed hydrology are described under land use, range-site condition, farm ponds, and floodwater-retarding structures. The extent of conservation measures such as waterways, terraces, gully stabilization, and strip cropping were not inventoried.

The topography of the study reach includes flat alluvium and uplands, rolling hills, and a portion of the Wichita Mountains. The slope is generally from northwest to southeast, with elevations ranging from 1,000 feet above mean sea level at Alex to about 1,700 feet above mean sea level at the upper ends of Sugar Creek and the Little Washita River.

The study reach includes 78 miles of Washita River channel having an average slope of 2 feet per mile. However, the valley between Anadarko and Alex is only about 30 miles long.

GEOLOGY

The drainage area of the Washita study reach is 1,130 square miles, of which 183 square miles (16.3 percent) is undifferentiated Quaternary age alluvium and terrace deposits. The remaining 947 square miles (83.7 percent) is Permian age sedimentary rock exposed at the surface, or near the

surface, covered by a thin layer of poorly developed soil. Figure 2-2 shows the distribution of geological formations in the study area.

The major ground-water aquifers having some potential and those having existing irrigation water-supply capability are the Permian age Rush Springs sandstone, which outcrops primarily in the western one-third of the study area, and the unconsolidated sands and gravels along the surface-water courses of the Washita River's main stem and tributaries.

Tables 2-1 and 2-2 show that approximately 240 square miles (21.3 percent) of the study area are underlain by Permian age Rush Springs sandstone. This formation has weathered, having thinned from west to east. Irrigation wells within the study area have capabilities of less than 100 gallons per minute. However, thicker sections west of the study area yield as much as 1,000 gallons per minute and average about 400 gallons per minute. Principal crops produced, using irrigation water from the formation, are peanuts and watermelons.

The horizontal and vertical variability of the Quaternary age alluvium and terrace deposits limit the usefulness of these deposits for irrigation supply. The producing sand and gravel deposits are lenticular and discontinuous in nature. However, saturated thicknesses averaging nearly 70 feet make possible some supplemental irrigation along the flood plain of the Washita River. Alfalfa and peanuts are the primary crops irrigated by these flood-plain wells.

The Cloud Chief (Pcc) formation, Marlow (Pmdb upper) formation, and Dog Creek shale-Blaine (Pmdb lower) formation are Permian age sedimentary deposits. These formations are described in table 2-3. They contain evaporites, i.e., gypsum, halite, and epsomite, that make the ground water produced from these formations unsuitable

(Continued on page 8.)

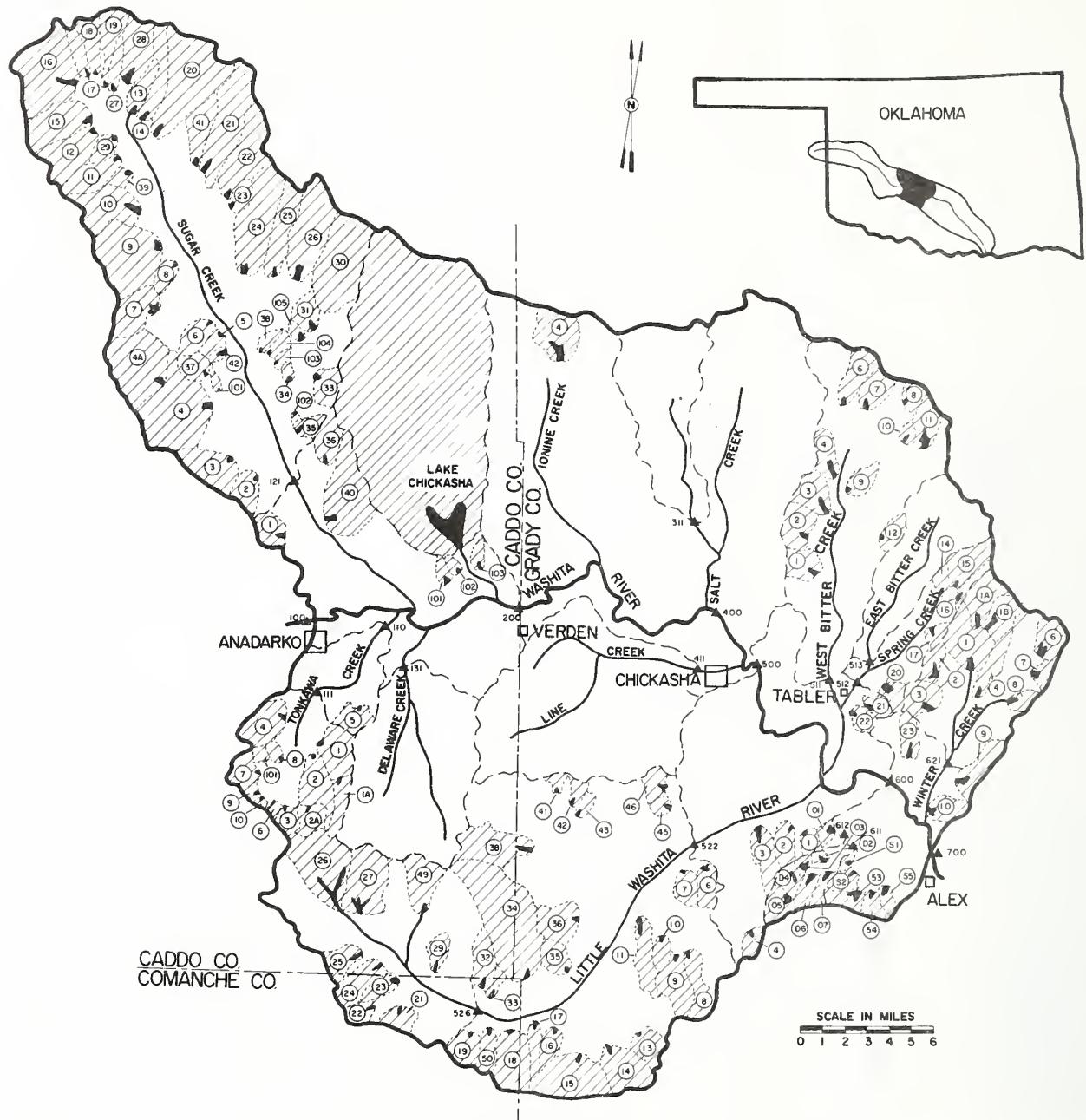


FIGURE 2-1.—Study reach of Washita River basin. Shaded areas represent areas controlled by floodwater-retarding impoundment structures, small black areas represent sediment pools, circled numbers represent impoundment sites, and uncircled numbers represent test-station locations.

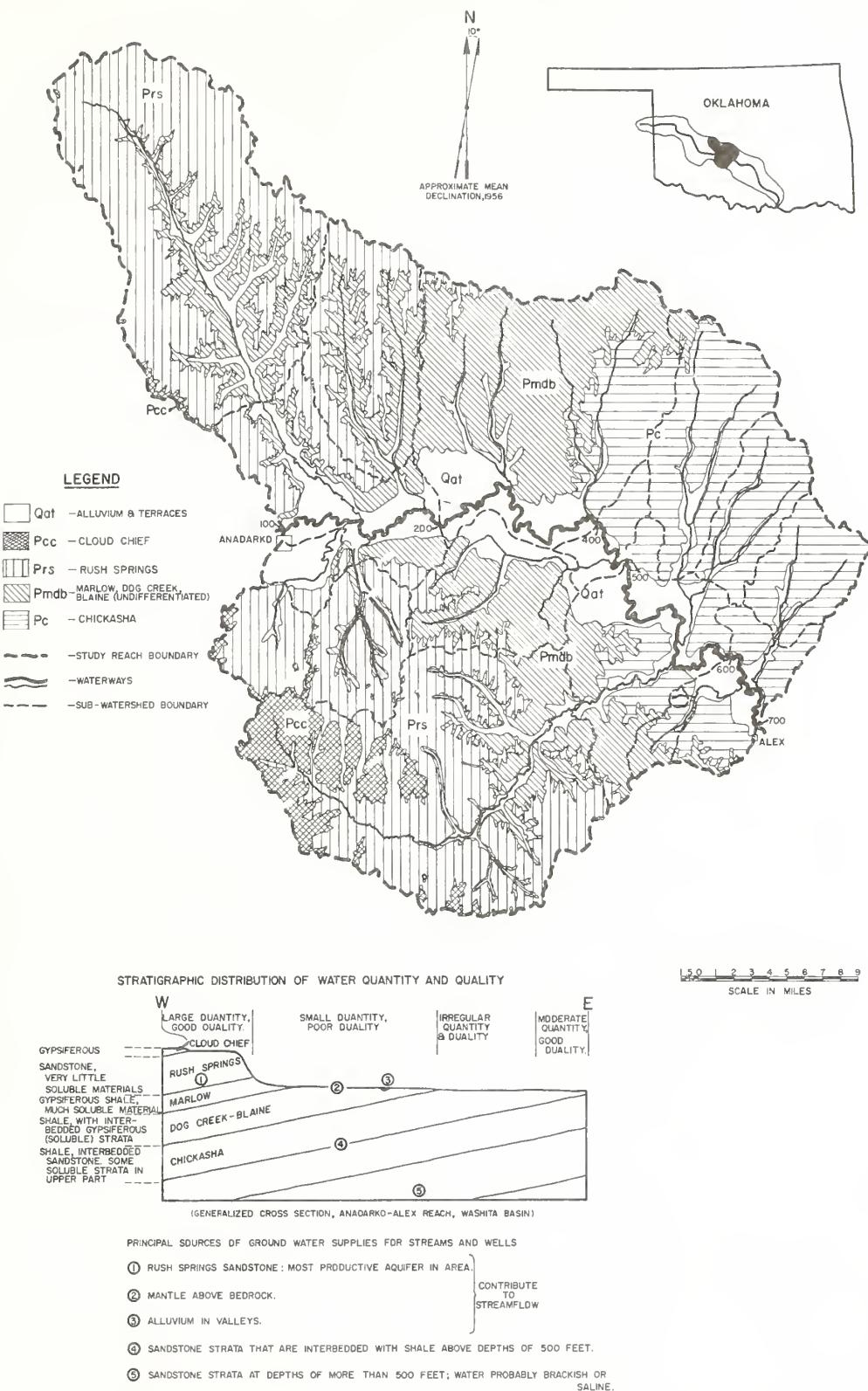


FIGURE 2-2.—Distribution of geological formations in study reach. Source: Davis 1955, Mogg et al. 1960, Tanaka and Davis 1963.

Table 2-1.—Geology of 1,130-square-mile study reach between main stem gaging stations

Station intervening area	Test station number	Drainage area (mi ²)	Percentage of drainage area underlain by—				
			Alluvium and terrace deposits	Cloud Chief formation	Rush Springs sandstone	Marlow formation, Dog Creek shale-Blaine formation	Chickasha formation
Anadarko to Verden ¹	100-200	426.3	14.4	1.4	61.7	22.5	0.0
Verden to Chickasha ²	200-400	176.4	21.1	0.0	2.0	57.3	19.6
Chickasha to Chickasha ³	400-500	68.5	28.7	0.0	13.0	47.1	11.2
Chickasha to Tabler ⁴	500-600	379.8	13.4	11.5	29.7	16.7	28.7
Tabler to Alex ⁵	600-700	79.4	17.9	0.0	0.0	3.2	78.9
Study reach		19.1		2.6	21.3	29.4	27.6

¹Includes Tonkawa (110, 111), Sugar (121), Delaware (131), and Spring (141) Creeks and ungaaged area (100 to 200).²Chickasha 4th St. station; area includes Salt Creek (311) and ungaaged area (200 to 400).³4th St. station to turnpike station; area includes Line Creek (411) and ungaaged area (400 to 500).⁴Chickasha turnpike station; area includes West Bitter (511) and East Bitter (512) Creeks, Little Washita River (522), and ungaaged area (500 to 600).⁵Includes Big Dry (611), Little Dry (612), and Winter (621) Creeks and ungaaged area (600 to 700).

Sources: Davis 1955, Mogg et al. 1960, Tanaka and Davis 1963.

Table 2-2.—Geology of tributary drainage areas in study reach

Station location	Test station number	Percentage of drainage area underlain by—				
		Alluvium and terrace deposits	Cloud Chief formation	Rush Springs sandstone	Marlow formation, Dog Creek shale-Blaine formation	Chickasha formation
Tonkawa	110	25.5	6.7	66.4	1.4	0.0
Tonkawa	111	4.3	10.3	85.4	0.0	0.0
Sugar	121	9.1	1.1	72.1	17.7	0.0
Delaware	131	9.7	3.4	84.5	2.4	0.0
Ungaged area	100-200	54.0	1.0	22.0	23.0	0.0
Salt	311	4.0	0.0	0.0	90.0	6.0
Line	411	22.8	0.0	18.6	58.6	0.0
Ungaged area	200-500	28.7	0.0	13.0	47.1	11.2
West Bitter	511	15.0	0.0	0.0	2.5	82.5
East Bitter	512	9.7	0.0	0.0	0.0	90.3
Little Washita	522	6.2	21.1	54.4	18.3	0.0
Dry	611	4.0	0.0	0.0	58.0	38.0
Dry	612	0.0	0.0	0.0	0.0	100.0
Winter	621	7.8	0.0	0.0	0.0	92.2

Sources: Davis 1955, Mogg et al. 1960, Tanaka and Davis 1963.

Table 2-3.—Stratigraphy of study reach¹

Group	Formation and map symbol ¹	Approximate thickness (ft)	Description
QUATERNARY SYSTEM			
	Alluvium and Terrace deposits, Qat	0-100	Silt, clay, fine sand, and some gravel; unconsolidated deposits in Washita and tributary valleys; maximum well yield about 200 gal/min.; water generally very hard; relatively soft water (less than 400 p/m total hardness) occurs in upper terrace along Washita, in extreme upper end of tributary valleys near Rush Springs formation and in East Bitter and Winter Creek valleys.
PERMIAN SYSTEM			
White Horse	Cloud Chief, Pcc	0-25	Gypsum and interbedded shale; contains very little water; well drained by underlying permeable Rush Springs sandstone; solution of gypsum contributes to hardness of local surface and ground water.
	Rush Springs sandstone, Prs	0-200	Fine-grained sandstone; cross-bedded and even-bedded; most important aquifer in area; supplies as much as 500 gal/min to irrigation wells; in most areas provides relatively soft, potable water.
	Marlow, upper part of Pmdb	0-100	Shale, siltstone, fine-grained gypsumiferous sandstone; Verden sandstone member, near the middle forms cap rock of buttes and small hills; contains very little highly mineralized water.
E1 Reno	Dog Creek shale and Blaine, lower part of Pmdb	0-200	Shale, interbedded with some gypsum and fine-grained gypsumiferous sandstone; contains small amount of water; water from gypsumiferous zones highly mineralized.
	Chickasha, Pc	100-250	Mixture of cross-bedded shales, siltstones, sandstones, and conglomerates; contains moderate amount of water (wells yield as much as 50 gal/min); water locally may be highly mineralized but generally of better quality than water in other formations, except Rush Springs and certain alluvial deposits.

¹The axis of the northwest-plunging Anadarko syncline bisects the area. Generally, in the northern part the rocks dip to the southwest, and in the southern part they dip to the north. Some jointing but no faulting has been observed. Available information indicates that surface-water and ground-water divides around reach nearly coincide; apparently there are no appreciable ground-water flows into or out of reach except as underflow through Washita valley alluvium.

Source: Davis 1955.

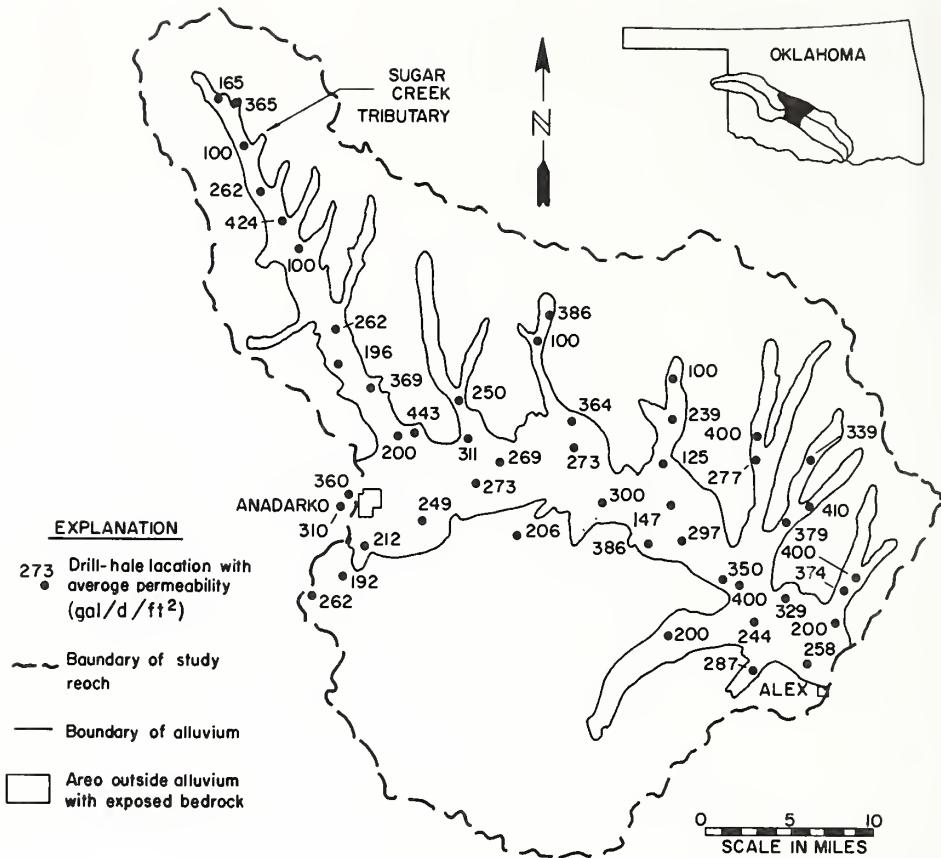


FIGURE 2-3.—Average saturated permeability of alluvial materials within study reach.

for domestic use and undesirable for stock wells in much of the study area underlain by these deposits.

The Chickasha formation (Pc) is a Permian age sedimentary deposit consisting of interbedded siltstone, mudstone, and sandstone. The sandstone occurs as discontinuous lenses capable of yielding small quantities of good quality water. The distributive nature of the lenticular sands in the Chickasha formation restricts the maximum yield of wells to about 50 gallons per minute. Therefore, use of the water is limited to domestic and stock wells only.

Figure 2-3 shows the distribution of permeability coefficients in the alluvial materials within the study reach. These coefficients are more than 10 times greater than those within the red beds (Naney et al. 1976). Measured coefficients of permeability within the Rush Springs sandstone are less than 50 gallons per day per square foot. There is, however, significant jointing and

cracking of the sandstone, which, along with increasing saturated thickness to the west, provide the well yields described above (400–500 gallons per minute).

GEOMORPHOLOGY

Observations and research on the central basin of the Washita River show that it is quite different from other Oklahoma rivers. These differences are expressed in the depth, texture, and fertility of the alluvium. The fine texture and high fertility of the alluvium are apparently due to the nature of the Permian materials of the Washita River basin. The fine texture of the source of the alluvium may partially explain its great depth (Goss et al. 1972).

The presence of high-level quartzitic terraces and materials in the lower part of the recent alluvium indicates that the Ogallala formation

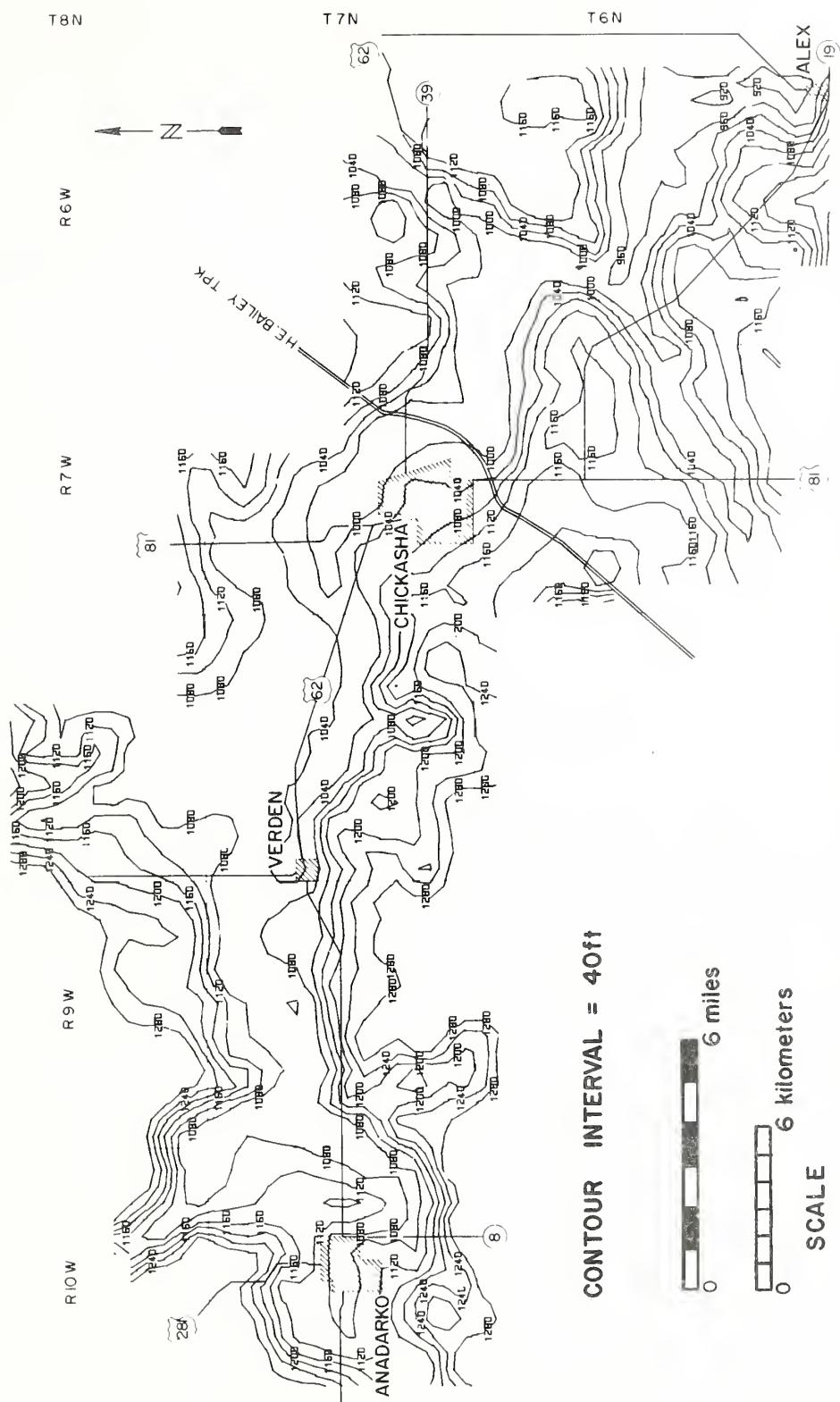


FIGURE 2-4.—Computerized bedrock surface map of main stem of Washita River within study reach. Numbers indicate feet above mean sea level.

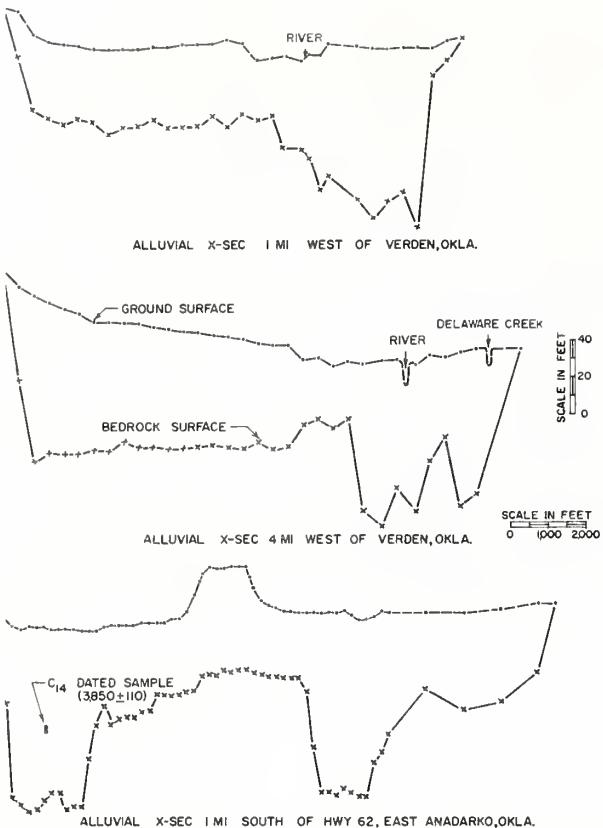


FIGURE 2-5.—Cross sections of Washita River alluvium.

may have extended as far east as Grady County. The sequence of events that produced the present Washita River apparently began in the late Pliocene period when the river cut through the Ogallala. By the late Pleistocene period, the river had cut to its maximum depth and had the characteristics of a mature river. During the late Pleistocene period, one or more periods of rejuvenation occurred, producing a deep, narrow valley in the bedrock. About 11,000 to 15,000 years ago, the Washita River began to aggrade. The two resulting terraces indicate that at least two major degradational periods have occurred. The terraces are too young to indicate whether these periods were associated with Pleistocene climatic changes. However, they may have been associated with recent climatic changes. Including the degradational periods, the mean rate of aggradation was about 0.0072 foot per year.

Data from the test-hole and observation-well drilling program were used to develop the computerized bedrock topographic map shown in figure 2-4. The channel configuration in the

bedrock is similar to the existing channel in the flood plain, except in the area 1 mile east and 1.5 miles southeast of Anadarko. The present channel is north and east of Anadarko, whereas the bedrock channel is southeast of Anadarko. Sediments in this segment of the alluvium are more than 100 feet thick and contain coarse sands and gravels near the bedrock contact with the alluvial materials.

Figure 2-5 illustrates the presence of bedrock terraces and deep alluvial valleys along the main stem of the Washita River. Most of the sites that have been core-drilled in the flood plain have indicated that a layer of quartz cobbles (3-4 inches in diameter) is present at the bedrock contact. Similar cobbles are also found near some of the watershed divides between the tributaries of the Washita River. These cobbles are the remnants of an older terrace; whereas, the younger terrace at the elevation of the current flood plain is composed of finer sands, silts, and clays. The finer sands and silts associated with the cobbles at the bedrock surface, i.e., the matrix in which the cobbles are found, preclude the use of the cobble zone as a supply of ground water.

SOILS

The Washita River research watershed from Anadarko to Alex drains portions of Caddo and Grady Counties and a very small portion of Comanche County. Most of the watershed is within the Cross Timbers and Reddish Prairie land resource areas (fig. 2-6). The Cross Timbers area is characterized by rolling to hilly sandstone uplands covered with scrubby post and blackjack oaks. The soils there are generally light colored and moderately acid, with reddish sandy clay loam subsoils, and are generally low in fertility. The Reddish Prairie is an area of smooth to rolling topography composed of alternating clayey red beds, sandy shales, and sandstones. The native vegetation is a mixture of grasses. The soils are loamy at the surface, with loamy to clayey subsoils. The soils vary from high to low in phosphate and from moderate to low in nitrogen.

Approximately 16 percent of the soils in the drainage area are alluvial flood-plain soils and 84 percent are upland soils. The flood-plain soils are grouped into three soil associations, one in Caddo County and two in Grady County. The upland soils are grouped into eight associations, three in

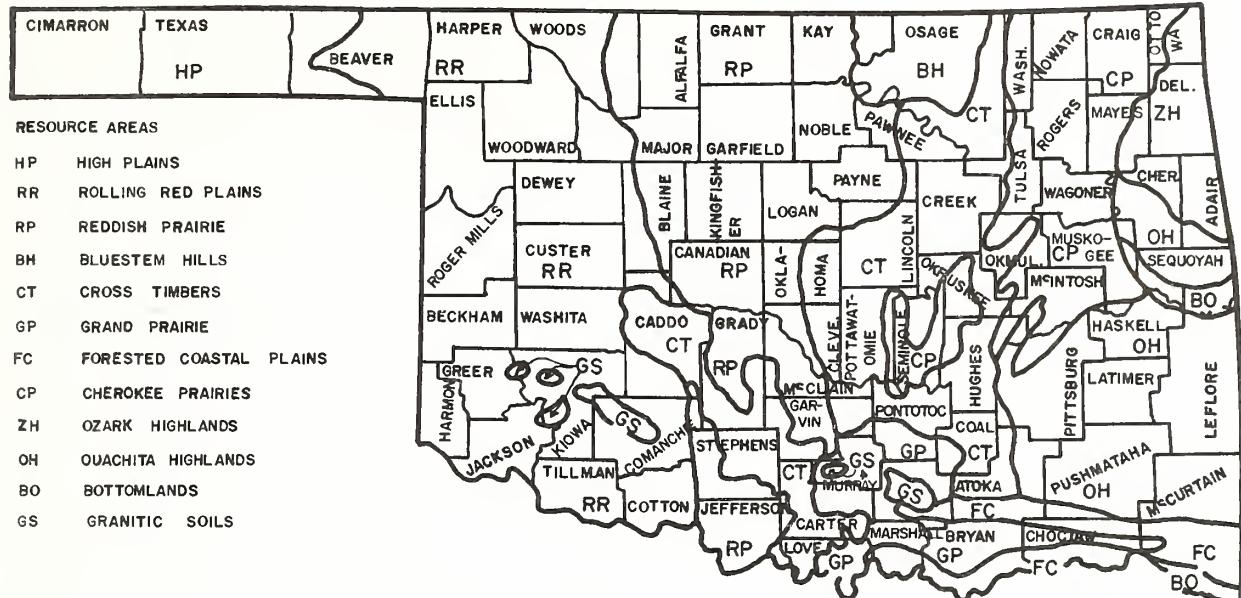


FIGURE 2-6.—Land resource areas in Oklahoma.

Table 2-4.—Characteristics of watershed soil associations

Soil association	Slope	Permeability (in/h)	Water-holding capacity (in/in)	Principal crops or use
FLOOD PLAIN SOILS				
Port-Gracemont-Pulaski	Nearly level	0.60-6.0	0.12-0.14	Alfalfa, small grains, cotton, peanuts, grain sorghum.
Port-Yohola-Gracemont	Nearly level	0.60-6.0	0.12-0.17	Do.
Dale-Reinach-McLain	Nearly level	0.06-2.0	0.12-0.24	Do.
UPLAND SOILS				
Renfrow-Kirkland-Bethany	Nearly level to gently sloping	<0.06-0.2	0.12-0.24	Wheat, cotton, grain sorghum, native grass.
Grant-Pond Creek-Lucien	Nearly level to sloping	0.2-6.0	0.10-0.24	Small grains, cotton, grain sorghum, peanuts, alfalfa.
Grant-Minco-Zaneis	Very gently sloping to sloping	0.2-2.0	0.11-0.24	Wheat, grain sorghum, cotton, tame pasture.
Stephenville-Noble- Windthorst	Very gently sloping to gently sloping	0.2-6.0	0.07-0.20	Tame pasture, native range.
Stephenville-Eufaula	Gently sloping to moderately steep	0.6-20.0	0.05-0.17	Do.
Nash-Lucien-Stephenville	Very gently sloping to moderately steep	0.6-6.0	0.10-0.24	Native range.
Dougherty-Eufaula	Very gently sloping to rolling	0.6-20.0	0.05-0.17	Grain sorghum, cotton, peanuts, small grains.
Noble-Darnell	Very gently sloping to hilly	2.0-6.0	0.11-0.17	Native range.

Table 2-5.—Taxonomic classification of soil series in research watershed

Series	Order	Subgroup	Family
Bethany	Mollisols	Pachic Argiustolls	Fine, mixed, thermic.
Dale	Mollisols	Pachic Haplustolls	Fine-silty, mixed, thermic.
Darnell	Inceptisols	Udic Ustochrepts	Loamy, siliceous, thermic, shallow.
Dougherty	Alfisols	Arenic Haplustalfs	Loamy, mixed, thermic.
Eufaula	Alfisols	Psammentic Paleustalfs	Sandy, siliceous, thermic.
Gracemont	Entisols	Aquic Udifluvents	Coarse-loamy, mixed (calcareous), thermic.
Grant	Mollisols	Udic Argiustolls	Fine-silty, mixed, thermic.
Kirkland	Mollisols	Udertic Paleustolls	Fine, mixed, thermic.
Lucien	Mollisols	Udic Haplustolls	Loamy, mixed, thermic, shallow.
McLain	Mollisols	Pachic Argiustolls	Fine, mixed, thermic.
Minco	Mollisols	Udic Haplustolls	Coarse-silty, mixed, thermic.
Nash	Mollisols	Udic Haplustolls	Coarse-silty, mixed, thermic.
Noble	Inceptisols	Udic Ustochrepts	Coarse-loamy, siliceous, thermic.
Pond Creek	Mollisols	Pachic Argiustolls	Fine-silty, mixed, thermic.
Port	Mollisols	Cumulic Haplustolls	Fine-silty, mixed, thermic.
Pulaski	Entisols	Typic Ustifluvents	Coarse-loamy, mixed, nonacid, thermic.
Reinach	Mollisols	Pachic Haplustolls	Coarse-silty, mixed, thermic.
Renfrow	Mollisols	Udertic Paleustolls	Fine, mixed, thermic.
Stephenville	Alfisols	Ultic Haplustalfs	Fine-loamy, siliceous, thermic.
Windthorst	Alfisols	Udic Paleustalfs	Fine, mixed, thermic.
Yohola	Entisols	Typic Ustifluvents	Coarse-loamy, mixed (calcareous), thermic.
Zaneis	Mollisols	Udic Argiustolls	Fine-loamy, mixed, thermic.

Caddo County and five in Grady County. The soil associations and some of their characteristics are given in table 2-4 (Bogard et al. 1978, Moffatt 1973). The taxonomic classifications for the major soil series are given in table 2-5 (U.S. Soil Conservation Service 1972).

LAND USE

Land use in the Washita study reach was documented in 1962, 1967, 1971, and 1974 to record changes that might be associated with observed hydrologic effects. In 1962 a complete inventory of the 1,130-square-mile study reach was made by aerial observation. An aerial point, sampling procedure was developed, tested, and used in the later surveys (Shockley and DeCoursey 1969). Each of five classifications of cultivated land, including sowed crop, summer sowed crop, alfalfa, row crop, and no crop, were planimetered from aerial photographs, and the remainder of the study reach was classified as rangeland. That method gave a classification for the study reach of 26 percent cultivated land and 74 percent rangeland. Rangeland was divided into 3 classifications and miscellaneous use into 11 classifications in the 1967, 1971, and 1974 inventories, as shown in table 2-6.

The land-use summary for the study reach shows a steady increase in sowed crop through the inventory period. Much of the increase in sowed crop was land that was formerly in cotton. The total row-crop acreage decreased by 50 percent in the 12 years from 1962 to 1974. The alfalfa acreage increased from 1962 to 1971 but then decreased by 40 percent between 1971 and 1974. Agricultural statistics compiled by the Oklahoma Crop and Livestock Reporting Service show a 41 percent decrease for alfalfa in Grady County from 1970 to 1974. However, a 65 percent increase in Caddo County is shown for those 4 years. Although the percentage of the study reach in alfalfa was small, a 40 percent decrease is about 25 square miles and could have a significant hydrologic effect on watersheds with large alluvial areas.

The other significant land-use change was in the timber and timbered pasture categories. Land use was classified as timber if the trees were so dense that no ground could be seen from the air. If grass could be seen growing between the trees, the use was classified as timbered pasture. Some of the tributary watersheds, including East and West Bitter Creeks and Salt Creek, had no significant timber. However, timbered pasture at Winter Creek decreased from 7 percent in 1967 to zero percent in 1974. Timbered pasture also

Table 2-6.—Land-use inventories
[Percentage of watershed area]

Watershed and drainage area (sq.mi.) Year	Cultivation		Range		Miscellaneous	
	Summer sowed crop	All fall crop	No crop	Total pasture	Grazed pasture	Total timber
Tonkawa (110) 2/ 13.3	25.22	6.42	1.37	39.43	.00	60.57
	25.69	.92	5.96	.00	42.20	2.29
	25.69	4.58	5.04	.00	45.86	2.75
	26.85	.92	5.55	6.01	.46	39.79
Tonkawa (111) 26.0	17.60	4.73	9.72	.39	32.44	.66
	19.67	10.90	2.63	1.97	4.07	19.57
	19.71	12.18	3.88	1.87	3.21	20.27
Sugar (121) 205.9	6.22	1.49	15.00	.00	22.71	1.74
	1967	6.49	2.70	3.11	12.70	25.13
Delaware (131) 40.1	6.39	1.47	9.30	.00	16.16	.00
	1967	5.38	2.18	1.74	3.92	13.80
	1971	7.86	6.99	2.47	3.93	11.36
Spring (141) 72.8	4.20	2.03	8.54	.13	14.90	.00
	1967	4.68	2.54	4.14	6.28	17.77
	1971	4.29	3.09	4.97	5.90	18.25
Washita (100-200) 72	21.70	7.23	11.40	1.51	41.84	.00
	1967	21.00	3.20	6.81	5.42	36.43
	1974	24.04	2.26	8.77	4.10	39.84
Salt (311) 23.76	23.75	3.86	3.75	1.36	32.72	.00
	1967	28.06	3.18	2.84	3.29	37.37
	1971	35.15	1.23	2.90	1.00	40.28
Line (411) 52.0	23.85	7.47	6.61	.14	38.07	.00
	1967	23.99	4.88	6.90	3.73	39.64
	1974	32.14	2.18	1.97	2.18	40.96
Total watershed area (sq.mi.)		25.22	6.42	1.37	39.43	.00
Total drainage area (sq.mi.)		25.69	.92	5.96	.00	42.20
Total watershed area (sq.mi.)		25.69	4.58	5.04	.00	45.86
Total drainage area (sq.mi.)		26.85	.92	5.55	6.01	39.79
Total watershed area (sq.mi.)		17.60	4.73	9.72	.39	32.44
Total drainage area (sq.mi.)		19.67	10.90	2.63	1.97	19.57
Total watershed area (sq.mi.)		19.71	12.18	3.88	1.87	3.21
Total drainage area (sq.mi.)		14.82	1.30	1.69	.91	18.98
Total watershed area (sq.mi.)		6.22	1.49	15.00	.00	22.71
Total drainage area (sq.mi.)		6.49	2.70	3.11	12.70	13.25
Total watershed area (sq.mi.)		5.78	4.03	4.16	11.36	12.74
Total drainage area (sq.mi.)		9.87	1.37	2.74	11.66	14.25
Total watershed area (sq.mi.)		6.39	1.47	9.30	.00	16.16
Total drainage area (sq.mi.)		5.38	2.18	1.74	3.92	11.36
Total watershed area (sq.mi.)		7.86	6.99	2.47	3.93	11.36
Total drainage area (sq.mi.)		10.85	.15	1.75	2.64	25.78
Total watershed area (sq.mi.)		4.20	2.03	8.54	.13	14.90
Total drainage area (sq.mi.)		4.68	2.54	4.14	6.28	17.77
Total watershed area (sq.mi.)		4.29	3.09	4.97	5.90	18.25
Total drainage area (sq.mi.)		10.67	.80	2.13	5.60	19.33
Total watershed area (sq.mi.)		21.70	7.23	11.40	1.51	41.84
Total drainage area (sq.mi.)		21.00	3.20	6.81	5.42	36.43
Total watershed area (sq.mi.)		24.04	2.26	8.77	4.10	39.84
Total drainage area (sq.mi.)		29.03	2.61	5.66	4.35	31.94
Total watershed area (sq.mi.)		23.75	3.86	3.75	1.36	32.72
Total drainage area (sq.mi.)		28.06	3.18	2.84	3.29	37.37
Total watershed area (sq.mi.)		34.30	2.18	1.97	2.18	40.84
Total watershed area (sq.mi.)		23.85	7.47	6.61	.14	38.07
Total drainage area (sq.mi.)		23.99	4.88	6.90	3.73	39.64
Total watershed area (sq.mi.)		32.14	2.18	1.97	2.18	40.96
Total watershed area (sq.mi.)		5.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
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Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total watershed area (sq.mi.)		25.23	1.45	1.45	1.45	1.45
Total drainage area (sq.mi.)		25.2				

Table 2-6.—Land-use inventories—Continued
[Percentage of watershed area]

Watershed and drainage area (sq mi.) Year	Cultivation										Miscellaneous								
	Range		Gullied pasture		Timbered pasture		Timber lot		Farm pond		Reservoir or detention creek		Private road		Highway (hard surface)		Urban rock		Total
Washita (200-500) ^{3/} 1962	25.34	7.57	4.41	.27	37.59	62.41	.69	.69	.55	1.38	.00	1.93	1.38	.27	.69	2.20	.69	10.47	
1967	28.24	5.23	7.16	3.44	.27	44.34	.96	41.48	2.75	45.19	.41	.82	.68	.00	2.60	1.37	.14	.69	1.92
1971	31.37	4.79	6.98	1.92	.41	45.47	.68	39.88	3.01	43.57	.25	.87	.37	.12	1.12	.87	.00	.75	1.99
1974	33.75	1.49	4.86	3.49	.50	44.09	.12	46.34	1.00	47.46	.37	1.49	.37	.12	1.12	.87	.00	.75	1.99
West Bitter (511) 1962	13.65	3.41	7.25	.14	24.45	75.55	.14	1.42	.28	.85	.00	1.70	1.00	.71	1.42	.14	.00	7.66	
1967	17.07	3.98	3.13	3.98	1.14	29.30	1.00	57.63	4.41	63.04	.00	1.14	.43	.43	.43	.14	.00	9.29	
1971	20.31	2.00	4.58	2.72	.14	29.75	.00	55.95	5.01	60.96	.00	1.71	.28	1.14	.57	.57	1.00	.28	
1974	21.65	1.42	2.56	2.99	.43	29.05	.14	60.99	.43	61.56	.00	1.71	.28	1.14	.57	.57	1.00	.28	
East Bitter (512) 1962	4.13	2.31	1.49	.00	7.93	92.07	.73	.15	.29	1.31	.29	.44	.44	.29	.00	.00	.00	6.56	
1967	4.08	1.02	3.80	.44	.15	9.49	1.75	75.92	6.28	83.95	.00	.40	.66	.40	.80	.13	.27	.00	
35.2	1971	4.93	2.80	3.20	.00	10.93	1.60	75.62	4.13	81.35	.00	.14	1.96	.00	3.65	.56	.56	.00	
1974	7.01	1.14	1.54	.84	.00	9.53	.14	80.52	2.24	82.90	.14	.28	.14	.14	.00	.00	.00	.14	
Little Washita (522) 1962	11.49	1.96	3.78	.52	17.75	82.25	.52	1.43	.52	.65	.13	3.74	1.30	.26	1.30	.13	2.07	16.85	
1967	9.47	2.33	2.85	2.20	.39	17.24	7.78	52.43	5.70	65.91	.39	.65	.39	.13	2.13	.91	.26	1.82	
1971	12.12	3.13	2.74	.78	.39	19.16	6.13	52.57	6.52	65.22	.13	1.24	.80	.13	1.24	.94	.00	1.34	
207.8	1974	12.85	1.74	1.47	1.74	.40	18.20	2.81	61.38	1.61	65.80	.56	.62	.80	.13	1.24	.94	.00	1.34
Washita (500-600) ^{3/} 1962	19.74	8.56	6.67	.72	35.69	64.31	.73	1.16	.29	.00	3.19	1.02	.43	.43	.02	.73	.00	10.17	
1967	16.86	3.05	11.77	5.52	.14	37.34	2.62	45.37	4.50	52.49	1.60	4.44	.44	.00	4.00	.58	.29	.87	
76	1971	18.75	4.07	10.32	3.92	.00	37.06	1.31	45.00	4.91	51.22	.44	1.45	.44	.00	4.00	.58	.29	
1974	22.98	1.29	4.53	6.80	.65	36.25	1.62	50.65	1.94	54.21	.65	1.29	.81	.65	.16	1.94	.97	.48	
Winter (621) 1962	3.68	3.56	1.35	.24	8.83	7.25	67.03	7.12	81.40	1.47	.37	1.35	.49	.37	.32	.86	.37	.49	
1967	3.68	2.98	2.46	1.06	.24	8.42	7.25	67.03	7.12	66.89	7.56	77.47	1.13	1.26	1.25	1.38	1.76	4.54	
33.3	1971	2.97	1.64	.88	.00	11.21	3.02	66.89	1.52	82.47	.25	1.39	.50	1.01	.50	2.40	.50	.25	
1974	8.09	.50	.88	.63	.25	10.35	.00	80.95	1.52	82.47	.25	1.39	.50	1.01	.50	2.40	.50	.25	
Washita (600-700) ^{3/} 1962	6.91	9.26	10.00	.29	26.46	4.56	65.77	7.35	73.54	.15	.44	.29	.29	.15	.88	.29	.44	.00	
1967	8.53	2.79	6.91	9.26	.00	27.49	5.00	56.21	7.34	64.77	.00	.57	.57	.72	2.74	.43	.29	.43	
38	1971	10.21	4.17	9.21	4.60	.14	28.33	2.16	55.27	7.34	64.77	.00	.57	.57	.43	2.74	.43	.43	.43
1974	13.48	.87	4.93	2.46	1.88	23.62	.72	69.32	.58	70.62	1.01	.87	.14	.43	.29	1.74	.14	.43	.43
Washita (100-700) ^{3/} 1962	13.79	4.54	6.98	.43	25.74	5.01	52.79	3.09	60.89	3.58	.80	.31	.76	.24	3.06	.88	.38	.43	
1967	13.85	2.86	4.70	4.66	.23	26.30	3.27	18.16	2.95	53.57	3.41	59.93	1.92	.81	.81	2.92	.87	.25	.85
1130	1971	3.52	5.18	3.27	.18	27.17	2.05	59.37	.95	62.37	2.12	1.05	.30	.98	.48	1.45	.66	.25	.62
1974	19.12	1.30	2.98	3.39	.38	27.17	2.05	59.37	.95	62.37	2.12	1.05	.30	.98	.48	1.45	.66	.25	.62

1/
2/ Dense timber with little or no forage growth.
Watershed area between stations 110 and 111.

3/
4/ Ungaged tributary area between river gaging stations.
Drainage area was changed from 201.5 to 203.9 sq. mi. January 1, 1968.

decreased significantly in the Tonkawa Creek, Delaware Creek, and Little Washita watersheds.

The accuracy of each land-use inventory was indicated by comparing the successive inventories of creeks, roads, and rocks, which should not have changed between surveys. Although installation of floodwater-retarding structures was continuing in the study reach from 1967 to 1974, the overall percentage of ponded water was shown to decline from 0.63 to 0.48 percent, which indicates some inaccuracy in the inventory procedure.

RANGE-SITE CONDITION

During the early stages of the Washita research project, much thought was given to methods of classifying rangeland according to its potential for surface runoff and erosion. After consultations with Hank Leithhead and H. N. Stidham, range conservationists with the Soil Conservation Service (SCS), the SCS procedure of range-site classification or condition was adopted. The procedure is an agronomic classification and is not necessarily related to runoff potential. Simply defined, range sites are distinctive kinds of rangeland with different potentials for producing native plants. The potential for production depends on the combined effects of the peculiar soils and climate.

Distinctions between range sites are judged by (1) differences in the kinds or proportions of plants (decreasers, increasers, and invaders) that compose the potential plant community or (2) differences in the total production of vegetation when the composition of the potential plant community is essentially the same. The distinctions between the four range-condition classes (U.S. Soil Conservation Service 1961) are indicated below.

Range-condition class	Percentage of present composition having potential for site
Excellent	76-100
Good	51-75
Fair	26-50
Poor	0-25

Most of the watersheds were classified by a sampling procedure between 1954 and 1969. Thus, only spatial variability was determined; temporal variation was thought to be small. Results of the survey are shown in table 2-7. Comparison of the data among watersheds shows that the East Bitter watershed had the best rangeland and the Delaware watershed the poorest.

Table 2-7.—Percentage of watershed rangeland classified in given range-site conditions between 1954 and 1969

Watershed	Test station number ¹	Range-condition class			
		Excellent	Good	Fair	Poor
Tonkawa Creek.....	110	.....	3	32	65
Sugar Creek.....	121	1	5	39	55
Delaware Creek.....	131	.....	5	18	77
Sugar Creek.....	141	1	7	24	68
Anadarko to Verden ²	100-200	2	6	33	59
Salt Creek.....	311	.....	10	87	3
Line Creek.....	411	1	8	82	9
Verden to Chickasha ³	200-500	1	10	80	9
West Bitter Creek.....	511	.....	21	75	4
East Bitter Creek.....	512	4	32	62	2
Little Washita River.....	522	2	10	47	41
Winter Creek.....	621	3	12	72	13
Chickasha to Alex.....	500-700	1	27	60	12
Study reach.....		1	11	52	36

¹See figure 2-1 for test station locations.

²Ungaged area.

³Verden to Chickasha turnpike station; ungaged area.

Table 2-8—Watershed and farm-pond drainage areas in 1962

Station location	Test station number ¹	Water-shed area (mi ²)	Farm-pond area (mi ²)	Percentage of total area
Anadarko	100	.....	.....	.....
Tonkawa, lower	110, 111	13.3	1.515	11.4
Tonkawa, upper	111	26.0	6.86	26.4
Sugar	121	201.5	42.7	21.2
Delaware	131	40.1	3.39	8.45
Spring	141	73.8	16.71	22.7
Anadarko to Verden ²	100-200	72.0	13.76	19.1
Salt	311	23.8	9.67	40.7
Verden to Chickasha ³	200-400	152.6	48.5	32.0
Line	411	52.0	18.42	34.5
Chickasha to Chickasha ⁴	400-500	15.1	4.54	30.1
West Bitter	511	59.4	20.90	34.4
East Bitter	512	35.2	10.68	30.4
Little Washita	522	207.8	40.5	19.5
Chickasha to Tabler ²	500-600	75.7	21.26	28.1
Big Dry	611	7.57	2.371	31.3
Little Dry	612	.880	.1820	20.7
Winter	621	33.3	6.85	20.6
Tabler to Alex ²	600-700	37.6	4.92	13.1
Accumulated totals:				
Anadarko	100	.....	.....	.....
Verden	200	426.3	85.0	19.9
Chickasha:				
4th St.	400	602.7	143.2	23.8
Turnpike	500	671.2	166.2	29.8
Tabler	600	1,051.0	259.3	24.7
Alex	700	1,130.4	273.7	24.2

¹See figure 2-1 for test station locations.²Ungaged area.³Chickasha 4th St. station; ungaged area.⁴4th St. station to turnpike station; ungaged area.

FARM PONDS

Storage of water in farm ponds is a difficult problem in hydrologic modeling. The drainage area of a watershed may vary from 100 percent to the percentage of the total drainage area downstream from farm ponds. For example, the drainage area of Salt Creek (311) during a runoff event may be as little as 60 percent of the total drainage area if none of the farm ponds fill. The drainage area of each watershed and the percentage of total drainage area controlled by farm ponds in 1962 are shown in table 2-8.

About 5 percent of the farm ponds on each tributary watershed were selected for observation of water level. One of four categories was assigned to each observation as follows: overflow-

ing, full, partly full, or empty. The observations were made soon after each runoff event and at least once each month from 1966 through 1972, inclusive. From these observations a continuous estimate of the percentage of drainage area contributing to runoff was compiled for each watershed and published in annual research reports. However, these data have not as yet been assessed for their impact on runoff. Additional modeling technology will be required to incorporate such data into current hydrologic models.

Periodic staff-gage readings were made at most of the ponds on the subdivided Spring Creek watershed upstream from station 141. Those records are under analysis, and the results will be published in a separate report.

Table 2-9.—Floodwater-retarding structures completed by January 1, 1979¹

Site No.	Area (acres)	Year Compl.	Site No.	Area (acres)	Year Compl.	Site No.	Area (acres)	Year Compl.
<u>SUGAR CREEK</u>			<u>TONKAWA CREEK</u>			<u>LITTLE WASHITA RIVER</u>		
1	1,288	1970	1-A	1,092	1968	2	704	1969
2	942	67	1	2,336	69	3	1,683	76
3	2,413	67	2	1,749	70	4	826	76
4-A	5,235	69	2-A	1,108	70	6	691	69
4	3,036	70	3	706	70	7	851	73
5	519	63	4	1,830	69	9	1,638	69
6	1,024	63	5	857	69	10	339	69
7	1,485	63	6	204	68	11	1,322	73
8	873	63	7	977	69	13	966	77
9	4,615	63	8	400	69	14	2,797	77
10	2,605	63	9	425	69	15	3,456	77
11	1,342	62	10	195	68	16	943	71
12	2,173	64	101	213	69	17	502	70
13	1,275	64	Total	12,092		18	3,233	72
14	1,252	63				19	1,060	77
15	2,452	64	<u>WINTER CREEK</u>			21	748	70
16	4,578	63				22	826	77
17	695	63	1-A	1,800	1965	23	614	71
18	1,149	63	1-B	1,304	65	24	1,792	76
19	1,477	63	1	2,339	65	25	723	76
20	5,568	62	2	899	66	26	4,250	71
21	4,251	63	3	1,341	65	27	2,944	76
22	3,768	63	4	1,164	65	29	896	76
23	548	63	6	1,530	66	31	4,909	77
24	4,249	63	7	750	65	32	1,249	70
25	2,002	67	8	741	66	33	384	70
26	3,558	72	9	1,834	65	34	7,059	73
27	629	63	10	941	65	35	954	72
28	2,169	63	23	816	66	36	2,285	72
29	884	64	Total	15,459		38	2,362	71
30	4,791	69				39	1,562	78
31	729		<u>WEST BITTER CREEK</u>			41	512	69
33	1,184	67				42	480	69
34	301	66	1	1,434	1974	43	374	72
35	549	70	2	858	72	45	357	69
36	1,175	67	3	2,010	74	46	1,222	71
37	831	66	4	1,306	75	48	454	77
38	1,267	70	6	1,222	72	49	1,850	77
39	408	62	7	1,114	72	50	1,260	77
40	3,425	70	8-B	745	75	Total	61,077	
41	1,578	63	9	608	72			
42	220	66	10	314	74	<u>SOLDIER CREEK</u>		
101	204	61	11	902	74	S-1	266	1966
102	42	61	12	582	74	S-2	527	66
103	320	67	Total	11,095		S-3	852	66
104	360	55				S-4	615	66
105	262	67	<u>EAST BITTER CREEK</u>			S-5	277	66
Total	85,700		14	410	1973	106	95	66
<u>DELAWARE CREEK</u>			15	1,389	73	107	75	66
8	4,890	1978	16	627	73	Total	2,707	
108	10,960	78	17	589	73	<u>DRY CREEK</u>		
Total	15,850		20	915	74	D-1	340	1966
<u>SPRING CREEK</u>			21	448	74	D-2	320	66
1	47,230	1958	22	333	74	D-3	264	66
2	528	73	Total	4,711		D-4	652	66
102	320	71	<u>IONINE CREEK</u>			D-5	1,172	66
103	380	71	4	2,066		D-6	631	66
Total	47,758					D-7	1,039	66
						Total	4,418	

¹/ See figure 2-1 for impoundment locations.

FLOODWATER-RETARDING STRUCTURES

A floodwater-retarding structure generally controls runoff from an area greater than 500 acres, which is much larger than the usual farm pond drainage area of less than 120 acres. A floodwater-retarding structure always has a principal spillway for slow release of floodwater. Farm ponds usually do not have a principal spillway.

Installation of floodwater-retarding structures in the Anadarko-Alex study reach was begun in 1958 with the construction of Lake Chickasha. One hundred and fifty sites in the study reach, where easements could be obtained, had been completed by January 1, 1979. These included 138 floodwater-retarding structures, 11 grade-control structures, and 1 multipurpose structure. These structures control runoff from 387 square miles or 34 percent of the 1,130-square-mile study reach. The year of construction and the acreage controlled at each site within the study reach are shown in table 2-9. The farm-pond drainage areas shown in table 2-8 and the floodwater-retarding-structure drainage areas shown in table 2-9 were determined without regard to each other. Thus, the total drainage area controlled by these combined impoundments is greater than either of these drainage areas but much less than the sum of the two.

The location of each floodwater-retarding structure is shown in figure 2-1. Construction at three additional planned sites on Delaware Creek and at about eight sites on the Little Washita River will complete the project within the study reach. Runoff will then be controlled from 424 square miles or 37.5 percent of the study reach.

SUMMARY

Topography of the study reach includes flat alluvium and uplands, rolling hills, and a portion of the Wichita Mountains. Elevations range from 1,000 to 1,700 feet above mean sea level. The study reach includes 78 miles of Washita River channel, with an average slope of 2 feet per mile.

The geology of the 1,130-square-mile reach can be broken down by percentages as follows: alluvium and terrace deposits, 19.1; Cloud Chief formation, 2.6; Rush Springs sandstone, 21.3; Marlow formation, Dog Creek shale, and Blaine

formation, 29.4; and Chickasha formation, 27.6. Ground-water aquifers that have some irrigation-water supply capability include the Rush Springs sandstone and unconsolidated sand and gravel lenses in the alluvium. The Washita River alluvium has great depth, fine texture, and mostly high fertility.

Most of the watershed lies within the Cross Timbers and Reddish Prairie land resource areas. The Cross Timbers is rolling to hilly sandstone upland that was covered with scrubby post and blackjack oaks before agricultural activity was begun. The Reddish Prairie is composed of alternating clayey red beds, sandy shales, and sandstones and has a mixed grass cover.

The land use was documented four times during the study period. The study reach was about 26 percent cultivated land and 74 percent rangeland. The principal changes in land use were an increase in sowed crop from 14 to 19 percent, a decrease in row crop from 7 to 3.4 percent, and a decrease in timber and timber pasture from about 10 to 4 percent of the study reach.

Most of the tributary watersheds were classified according to range-site condition between 1954 and 1969. For the study reach, the classification by percentage was as follows: excellent, 1; good, 11; fair, 52; and poor, 36.

About 5 percent of the farm ponds on each tributary watershed were selected for monthly and after-storm observation of water level. These observations were made from 1966 through 1972, inclusively. A continuous estimate of the percentage of drainage area contributing to runoff was then compiled for each watershed.

Floodwater-retarding structures had been completed at 150 sites in the study reach by January 1, 1979. Construction at 11 additional sites will complete the project within the study reach. Runoff will then be controlled from 424 square miles or 37.5 percent of the study reach.

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Section 3.—Precipitation and Climate

INTRODUCTION

The rain-gage and associated-precipitation research program for the Southern Great Plains Watershed Research Center was planned and initiated in 1961. Beginning in May of that year, the first rain gages of a basic network of 168 gages were installed. The completed network covered 1,500 square miles of a central reach of the Washita River basin between Alex and Anadarko on the main stem of the river, including areas outside the study reach. Installation of the 168 gages was completed in October 1961. Since that time, the network has operated continuously, and the basic network has remained intact without changes in gage location. Additional gages were added on smaller subwatersheds within the area until a maximum of 230 gages were in operation in 1972 (fig. 3-1).

The objectives of the research associated with this rain-gage network were to (1) develop basic information on amounts, duration, areal and seasonal distributions, storm paths, and other characteristics of precipitation as affected by geographic location, topography, and other factors to the extent that these characteristics influence runoff from agricultural watersheds in the Washita River basin; (2) relate point precipitation measurements to mean precipitation on watersheds of various sizes; and (3) determine and evaluate precipitation parameters useful in estimating runoff.

The need for this research was based on "SCS Research Needs," paragraphs I-A-2-b and I-A-2-d, "Soil and Water Research Needs," 1960 addendum to 1958 report. This report states that "Procedures are needed for predicting dependable yields of water from watersheds of various sizes up to about a hundred square miles as well as for predicting the effect of upstream programs on the water yield at points further downstream where water supplies of larger water users and control structures may be affected."

Nearly 18 years (1961-78) of continuous records were collected from the basic gage network, supplying rainfall inputs to 50 drainage basins varying in size from 12 acres to 1,130 square miles. Numerous publications, including inhouse, technical society, and interagency publications and masters theses and doctoral dissertations, have been prepared using data from this research program.

PRECIPITATION CLIMATOLOGY

The network area is in a region of moist to dry subhumid climate. Normal annual precipitation, according to National Weather Service data, varies from 33 inches on the east edge of the network to 28 inches on the west edge. The normal for Chickasha, near the center of the area, is 31.60 inches. Annual precipitation totals at points in the watershed have been as large as 51 inches and as small as 13 inches. Distribution of precipitation throughout the year is bimodal, with peaks occurring in May and September. About 98 percent of the yearly precipitation occurs as rainfall, and the remaining 2 percent occurs as sleet and snow. Snow falls on the average of 5 days during the period from November through March and is not a factor contributing to flooding. Flooding can occur at any time during the year, but it is most frequent during late spring and early fall and is associated with thunderstorm rainfall.

The network lies between latitudes 34°45' and 35°30' and between longitudes 97°45' and 98°30'. The topography of this area is characterized by rolling plains cut by deeply eroded valleys. Maximum relief is approximately 450 feet, occurring in the northwest quadrant of the network between gages 13 and 104 (fig. 3-1). The predominant topographic features of the area are the Washita River and associated flood plains, which comprise 10 percent of the area.

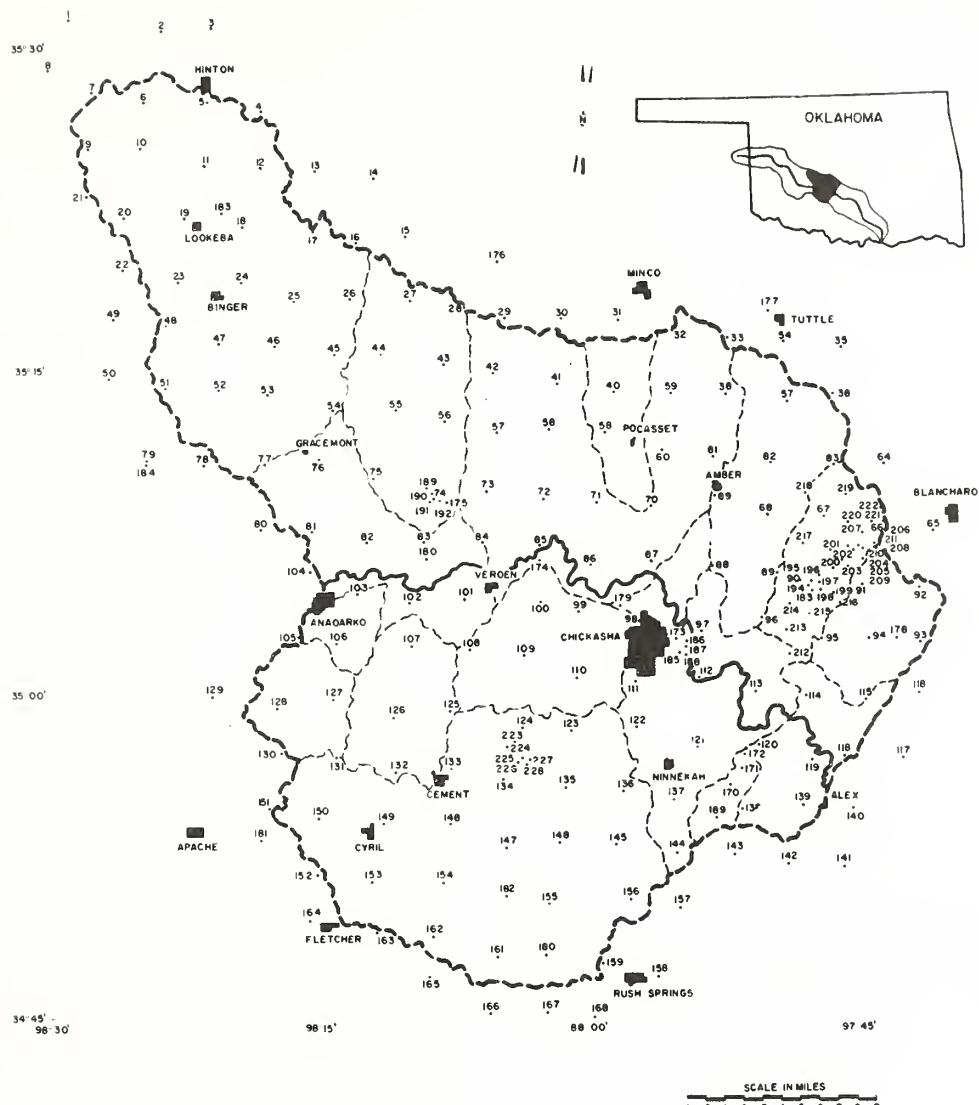


FIGURE 3-1.—Rain-gage locations and subdrainage basins in study reach.

DESIGN OF RAIN-GAGE NETWORK

The design, aimed largely at assessment of the rainfall input to the tributary areas, was based primarily on an analysis of data from a network on the Sandstone Creek watershed, a tributary area of the Washita River upstream from the

study area. Thirty-nine rain gages, fourteen recorders, and twenty-five standards were installed within or near the boundaries of the 100-square-mile Sandstone Creek watershed in 1951. Data from this network of gages, with a density of one gage per 2.6 square miles, were available for the period 1951-61. Graphical and statistical studies were made of methods of

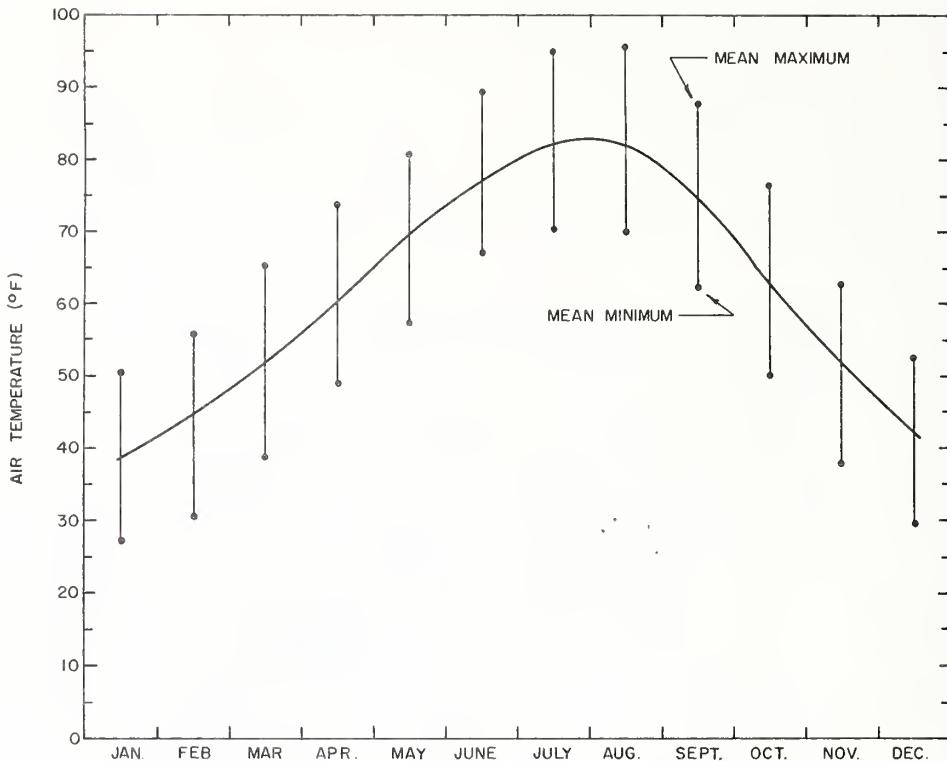


FIGURE 3-2.—Normal mean maximum and mean minimum air temperature, Chickasha, Okla., 1931-60.

Table 3-1.—Conversion ratios from sites in Oklahoma and Texas for converting Young's evaporation pan data to class A pan data

Month	Lake Hefner ¹	Texas ²	CRS ³
January	1.03	1.06	.....
February	1.46	1.56	.....
March	1.18	1.25	.....
April	1.30	1.26	1.72
May	1.47	1.52	1.60
June	1.46	1.52	1.60
July	1.46	1.47	1.56
August	1.47	1.49	1.71
September	1.40	1.39	1.66
October	1.31	1.33	1.32
November .....	.99	1.03	.....
December .....	.95	.96	.....

¹Source: U.S. Geological Survey 1954.

²Source: Texas Agricultural Experiment Station 1954.

³CRS, South Central Oklahoma Cotton Research Station. Class A pan data not available for months showing no data.

estimating precipitation on the watershed and of various gage densities and distributions.

Relatively small differences existed between watershed storm rainfall as determined from 39 gages and that determined from 19, 13, or 10 gages over 100 square miles, but the differences rose sharply when determinations were made from 5, 2, or 1 gages. This held true whether storms were large (≥ 0.80 inch) or small and whether the determination was made by simple averaging of the point rainfalls or by consideration of isohyetals.

This group also investigated the types of rain-gage distribution, i.e., uniform or random, that would most accurately assess rainfall and found that "uniformly geographically spaced rain gages apparently provide better estimates of precipitation on areas of a few score miles than an equal number of randomly spaced gages." This criterion, which is supported by the work of Linsley and Kohler (1951) in Ohio and Huff and Neil (1957) in Illinois, was also adopted for the basic network.

Consideration was given to the possibility that, if storm movements followed a consistent pat-

tern, the orientation and pattern of the rain-gage network might be designed to take this into account. For example, if storms moved from west to east, the north-south variability in magnitude might differ substantially from the east-west variability. Although there was indication that such a pattern did exist with some consistency in the region, it was considered desirable to have a square grid rather than a rectangular grid, with the thought that modifications could easily be made as more positive information accrued. The square design did fit in well with the road network, there being a farm-to-market road every mile—both east and west and north and south.

The ideal way to design a network is to saturate the area and then, from the mass of data, scale the network down to achieve just the desired degree of accuracy. But resources for such saturation are almost never available, and the design of most networks, including the one under discussion, is influenced substantially by economic considerations.

EVAPORATION DATA

Evaporation data have been collected on a regular basis at the Center since 1963. The data are measured at sunken Young's screened pans at rain-gage stations 90 and 124 (fig. 3-1) and at the South Central Oklahoma Cotton Research Station near gage 173. The Cotton Research Station

(CRS) record is the longest record of any of the three stations and is located within a National Weather Service climatic station enclosure adjacent to a class A pan.

Young's pan data recorded at CRS is continuous and could be used to fill missing gaps in the class A pan record. Ratios published in U.S. Geological Survey Professional Paper 269 (1954) can be used to convert Young's pan data to class A pan data. Ratios also have been published at sites in Texas (Texas Agricultural Experiment Station 1954). The ratios from these studies, as well as those ratios computed from available months at CRS, are given in table 3-1. There are no ratios listed at CRS for January, February, March, November, or December because no class A pan data were available for these months.

In addition to evaporation, wind and air temperature are also measured at the three climatic stations on a daily basis. Air temperature is a long-term record of more than 30 years. The normal mean temperature data from the Chickasha station for 1931-60 are shown in figure 3-2.

GENERAL CLIMATE RAINFALL

During nearly 18 years of network operation, some interesting observations of precipitation

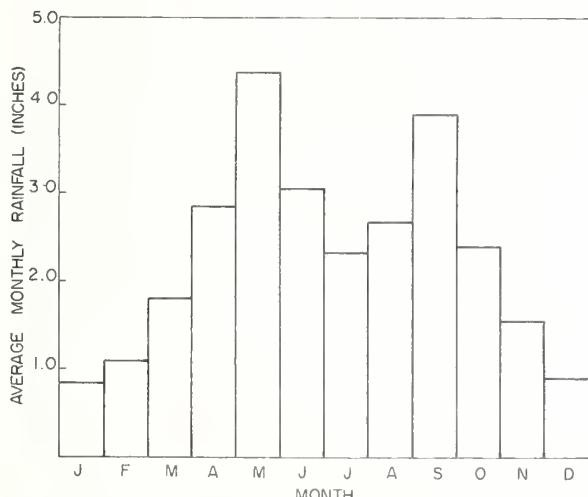


FIGURE 3-3.—Mean monthly distribution of rainfall for rain-gage network, 1962-77.

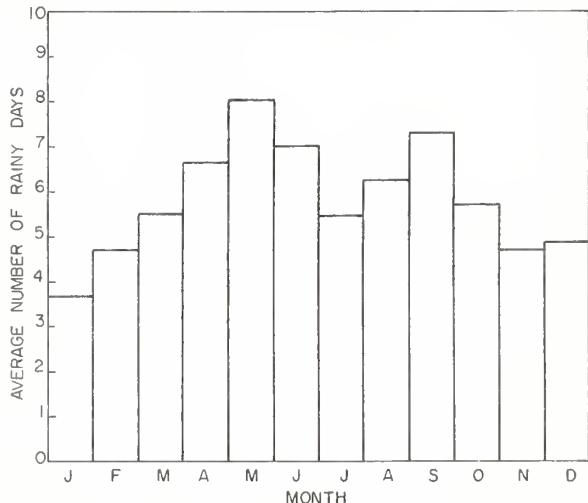


FIGURE 3-4.—Average number of rainy days per month for rain-gage network, 1962-77.

Table 3-2.—Average rainfall, in inches, for rain-gage network, 1962-77¹

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1962	0.38	0.81	0.83	2.39	2.68	7.82*	1.96	1.26	5.20*	2.53	1.33	1.25	28.44
1963	.23	.37	1.74	2.70	1.60	3.43	2.71*	1.08	2.19	.54	2.66*	.66	19.91
1964	.94	2.12*	1.20	1.27	5.97*	1.19	.84	3.97*	4.33*	.80	5.45*	.69	28.77
1965	1.05	.78	1.13	2.51	3.92	3.57	.82	5.16*	4.53*	1.49	.04	1.40	26.40
1966	.50	1.55*	1.04	3.72*	.87	2.06	1.34	5.93*	3.47*	.41	.49	.31	21.69
1967	.30	.10	2.13*	5.55*	3.24	2.44	2.22	1.14	5.24*	2.69	.29	1.07	26.41
1968	2.47*	1.26	1.38	2.56	5.57*	2.55	3.65*	2.01	3.80*	2.15	4.62	1.10	33.12*
1969	.50	2.06*	2.20*	2.24	5.63*	3.29	1.37	2.89*	4.50*	1.59	.18	1.01	27.46
1970	.11	.48	2.65*	3.25*	3.56*	2.19	1.45	1.25	5.25*	1.94	.66	.31	23.10
1971	.82	1.64	.07	.63	4.43	4.12	2.40	4.05*	4.92*	4.23*	.69	2.73*	30.73
1972	.12	.44	.48	3.72	3.20	1.10	1.22	1.75	.91	7.57*	2.18*	.73	23.42
1973	3.30*	.53	6.06*	2.78	4.37	4.77	4.58*	1.14	7.49	3.01	2.04*	.32	40.49*
1974	.12	1.92*	2.53*	3.47	4.17	1.80	1.23	4.98*	3.49	4.44*	1.97*	1.41	31.53
1975	2.11*	2.10*	2.03*	1.57	8.59*	3.78	7.24*	1.69	2.35	1.03	1.30	1.10	34.09*
1976	.00	.26	2.52*	5.02*	2.74	2.49	2.01	2.30	3.00	2.47	.06	.36	23.23
1977	.48	1.56	1.01	2.97	10.04*	2.08	2.16	2.94*	1.11	1.64	1.26	.12	27.37
Average	.84	1.12	1.81	2.90	4.42	3.04	2.32	2.72	3.87	2.41	1.58	.91	27.94
Normal ²	1.35	1.47	1.90	3.07	5.36	4.16	2.42	2.57	3.13	3.03	1.63	1.51	31.60

¹Normal rainfall based on Chickasha Weather Bureau record for 1931-60. Numbers followed by an asterisk indicate above normal rainfall.

²Normal mean-temperature data from Chickasha station for 1931-60.

Table 3-3.—Annual rainfall variation and distance between gaging stations, 1962-77

Year	Network average (in)	Maximum gage amount (in)	Minimum gage amount (in)	Difference (in)	Separation distance (mi)
1962	28.44	37.50	22.28	15.22	37
1963	19.91	27.87	14.65	13.22	34
1964	28.77	36.88	22.95	13.93	22
1965	26.40	37.72	19.72	18.00	30
1966	21.69	29.27	12.70	16.57	39
1967	26.41	33.23	21.23	12.00	39
1968	33.12	42.84	26.89	15.95	20
1969	27.46	35.38	20.79	14.59	23
1970	23.10	34.19	15.27	18.92	53
1971	30.73	38.67	24.05	14.62	30
1972	23.42	32.17	15.39	16.78	40
1973	40.49	51.47	34.37	17.10	21
1974	31.53	40.36	25.06	15.30	18
1975	34.89	45.14	29.81	16.33	19
1976	23.33	28.63	19.08	7.55	46
1977	27.37	36.57	21.00	15.57	31
Average	.....			15.00	31

characteristics were made. The average annual precipitation, determined from the network measurements from 1962 to 1977, was 27.94 inches (table 3-2). The areal distribution of recording rain gages is shown in figure 3-1. During this 191-month period, 137 months were below normal in rainfall. Only 3 years, 1968, 1973, and 1975, were above normal. The maximum precipitation at a rain-gage station during the period (table 3-3) was 51.47 inches (1973) and the minimum

was 12.70 inches (1966). Similar variations in annual point measurement were observed each year. The difference between the yearly network extremes averaged 15 inches. The distance between the stations having the most and the least rainfall averaged 31 miles. Results of a study (Nicks and Hartman 1966) indicate that such variations would not be expected from the usual climatological station spacing.

The average monthly rainfall distribution is

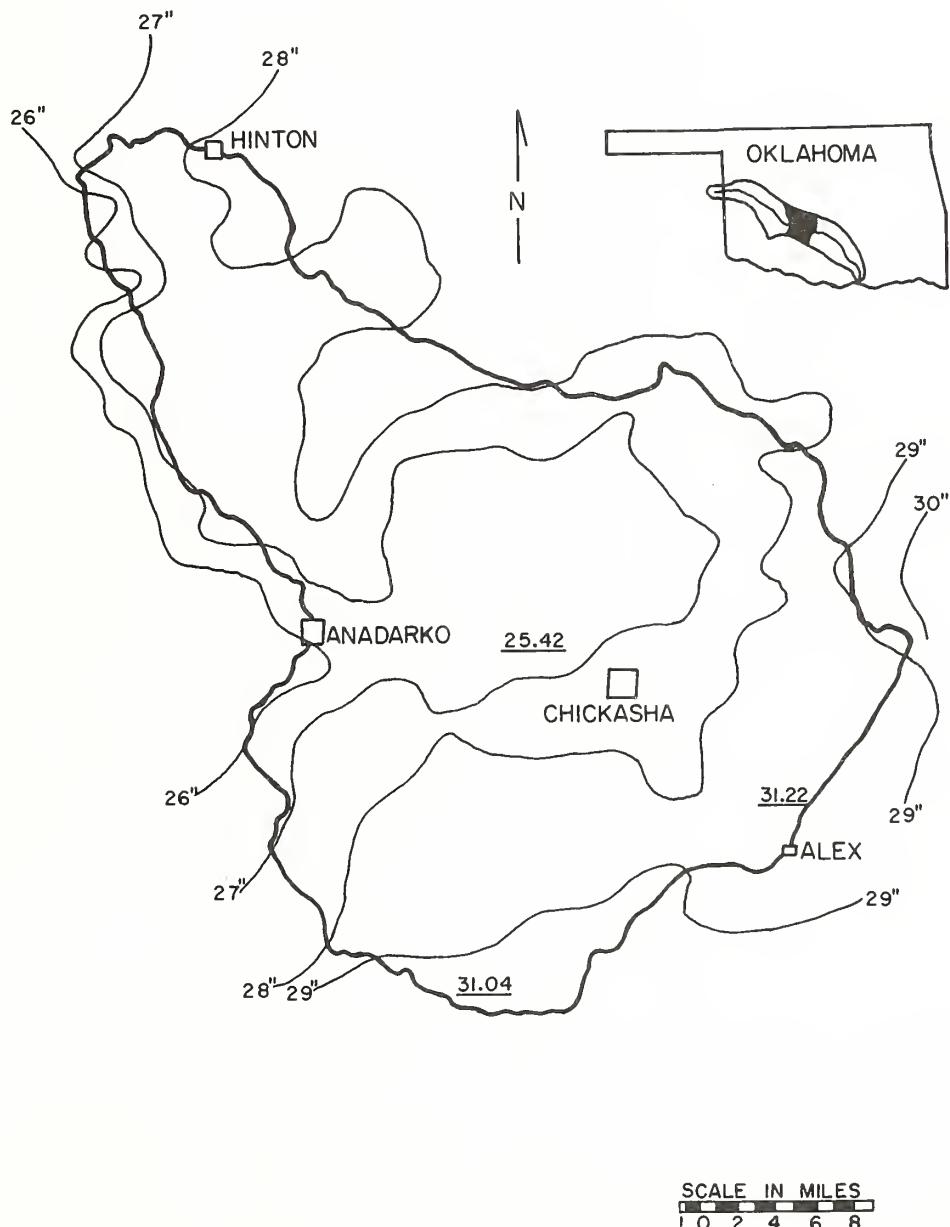


FIGURE 3-5.—Average annual distribution of rainfall for rain-gage network, 1962-77.

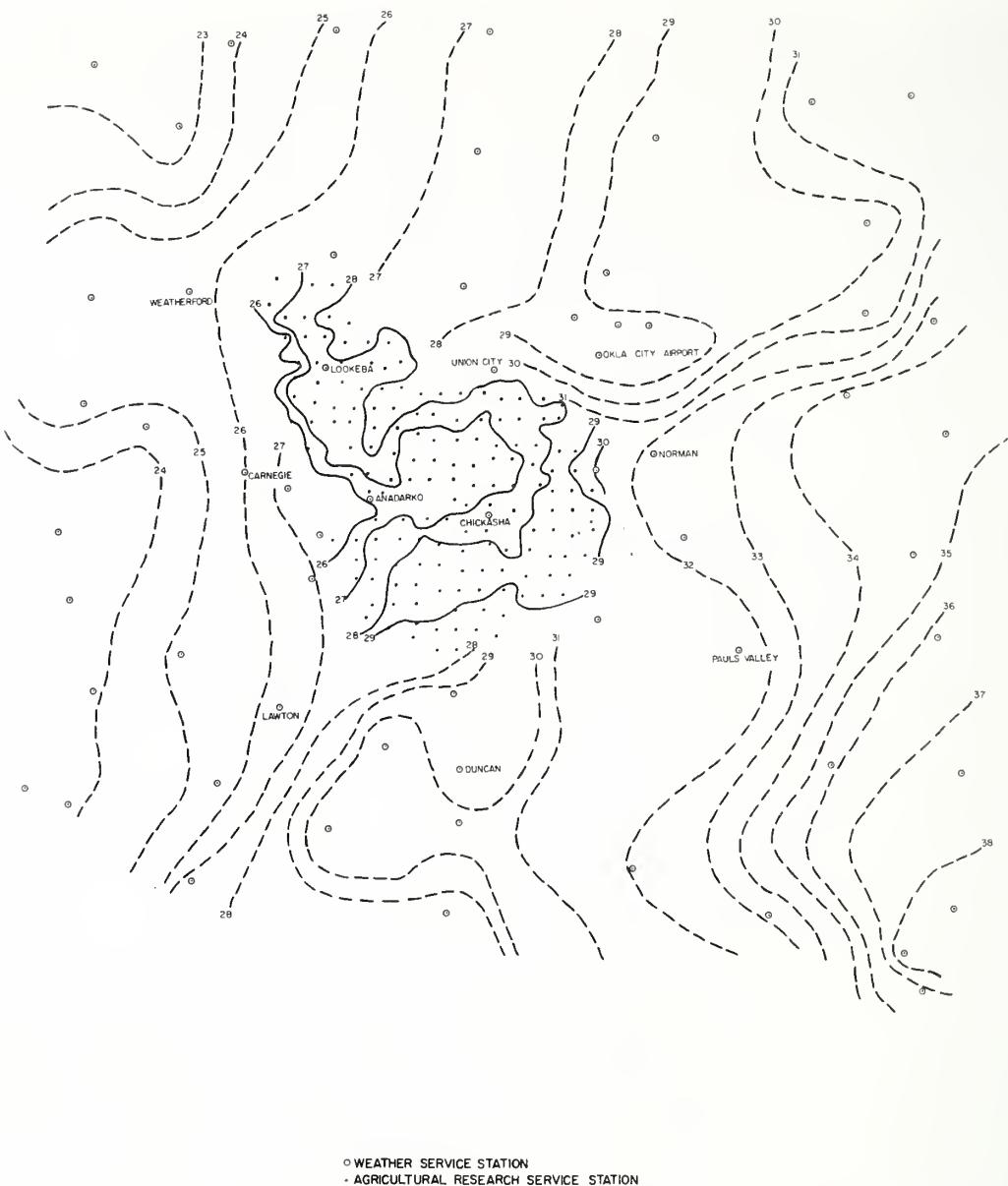


FIGURE 3-6.—Average annual distribution of rainfall for rain-gage network (1962-77) and normal annual rainfall for area surrounding network (1931-60).

shown in figure 3-3. The distribution is bimodal, with peaks in May and September. This same characteristic is also represented in the distribution of the average number of rainy days per month (fig. 3-4).

The annual rainfall distribution over the network is shown in figure 3-5. This distribution of annual isohyetal line can be compared with an an-

nual plotting of the normal rainfall (1931-60) for the portion of Oklahoma surrounding the network (fig. 3-6). The pattern for the 16 years of network data does not match the lines shown for the climatic station normal (30 years) isohyets. However, it might be expected that, with longer periods of record, the network pattern would conform more closely to the normal pattern.

STORM DATA

Several storms occurring during the period of network operation produced large point amounts (Hartman et al. 1969). Some of the larger storms are listed in table 3-4. The average return periods indicated for these storms are based on the data given in U.S. Weather Bureau Technical Paper 40

(Hershfield 1961). Return periods exceeding 100 years were experienced at 13 percent of the stations. However, the maximum recorded storm rainfall for 79 percent of the network stations was less than that for the 10-year storm, for 5 percent of the stations it was more than that for 10 but less than 50 years, and for 3 percent of the stations it was more than that for 50 but less than

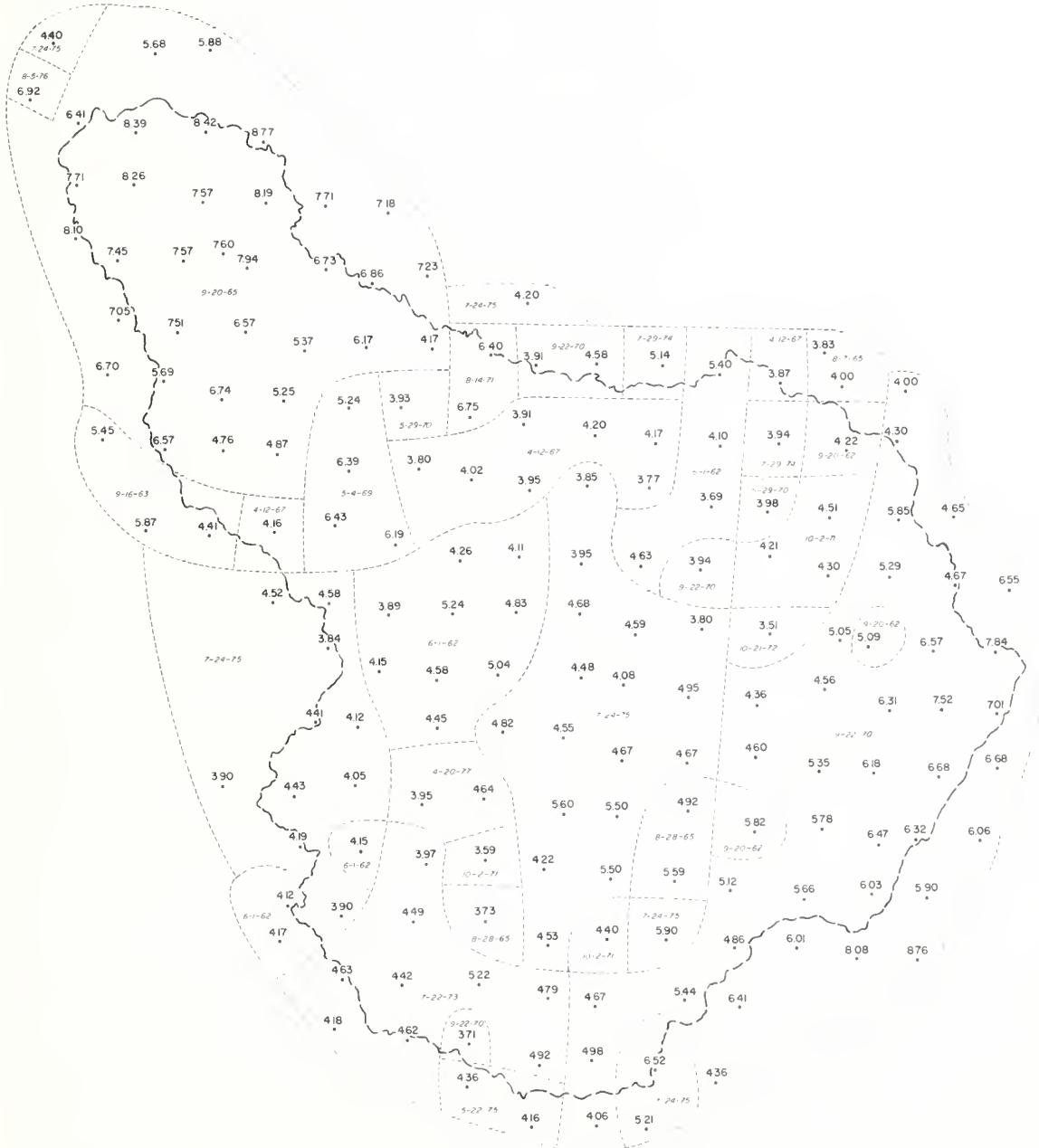


FIGURE 3-7.—Maximum daily rainfall and date of occurrence for each rain-gage station, 1962-77.

Table 3-4.—Summary of maximum storm rainfall in rain-gage network, 1962-77

Date	Amount (in)	Duration (h)	Average return period (yr)
June 1, 1962	5.40	12	15
Sept. 3, 1962	6.14	6	75
Sept. 20, 1962	5.82	10	25
June 23, 1963	5.76	8	30
Sept. 16, 1963	5.87	16	15
May 9, 1964	4.08	3	20
May 10, 1964	5.16	12	10
June 21, 1965	6.00	4	>100
Sept. 20, 1965	8.77	5	>100
June 8, 1966	3.72	2	20
Aug. 11, 1966	3.62	4	5
Apr. 12, 1967	4.34	6	10
Aug. 17, 1967	3.47	4	5
June 15, 1968	4.70	2	80
May 31, 1968	4.62	8	15
May 4, 1969	6.43	7	85
Sept. 21, 1969	4.11	9	10
May 29, 1970	4.25	3	30
Sept. 22, 1970	8.76	15	>100
Oct. 2, 1971	4.51	11	10
Oct. 30, 1972	4.88	17	10
July 9, 1972	3.11	4	5
July 22, 1973	5.22	4	60
Sept. 3, 1973	3.89	2	30
Aug. 9, 1974	5.80	3	>100
July 24, 1975	6.52	6	>100
Aug. 5, 1976	6.92	5	>100
May 20, 1977	5.78	4	>100

100 years. Figure 3-7 shows the maximum recorded 1-day rainfall for each station in the network.

Storm rainfall differences have also shown a high degree of variability. Differences of 4.5 inches in 6 miles have been observed in local and widespread storms. Yearly occurrence of such variation appears to be characteristic of rainfall for this region. Because of such large variation, a study was made to assess the adequacy of the network gages to measure daily rainfall (Nicks 1966). The results indicate that, at the 5-percent level, the average daily rainfall for the area computed from 5 gages was significantly different from that computed from 168 gages. At a density of 10 equally spaced gages over the watershed, there was no significant difference in the amount of rainfall. These results indicate that areal estimates of the daily rainfall for the 1,130-square-mile area (determined by the 168 gages)

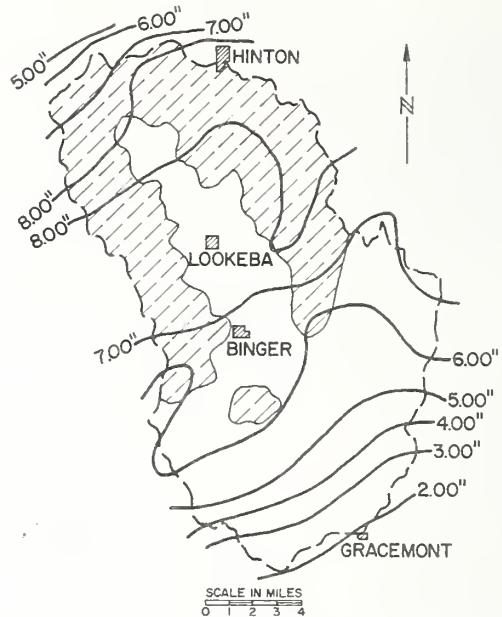
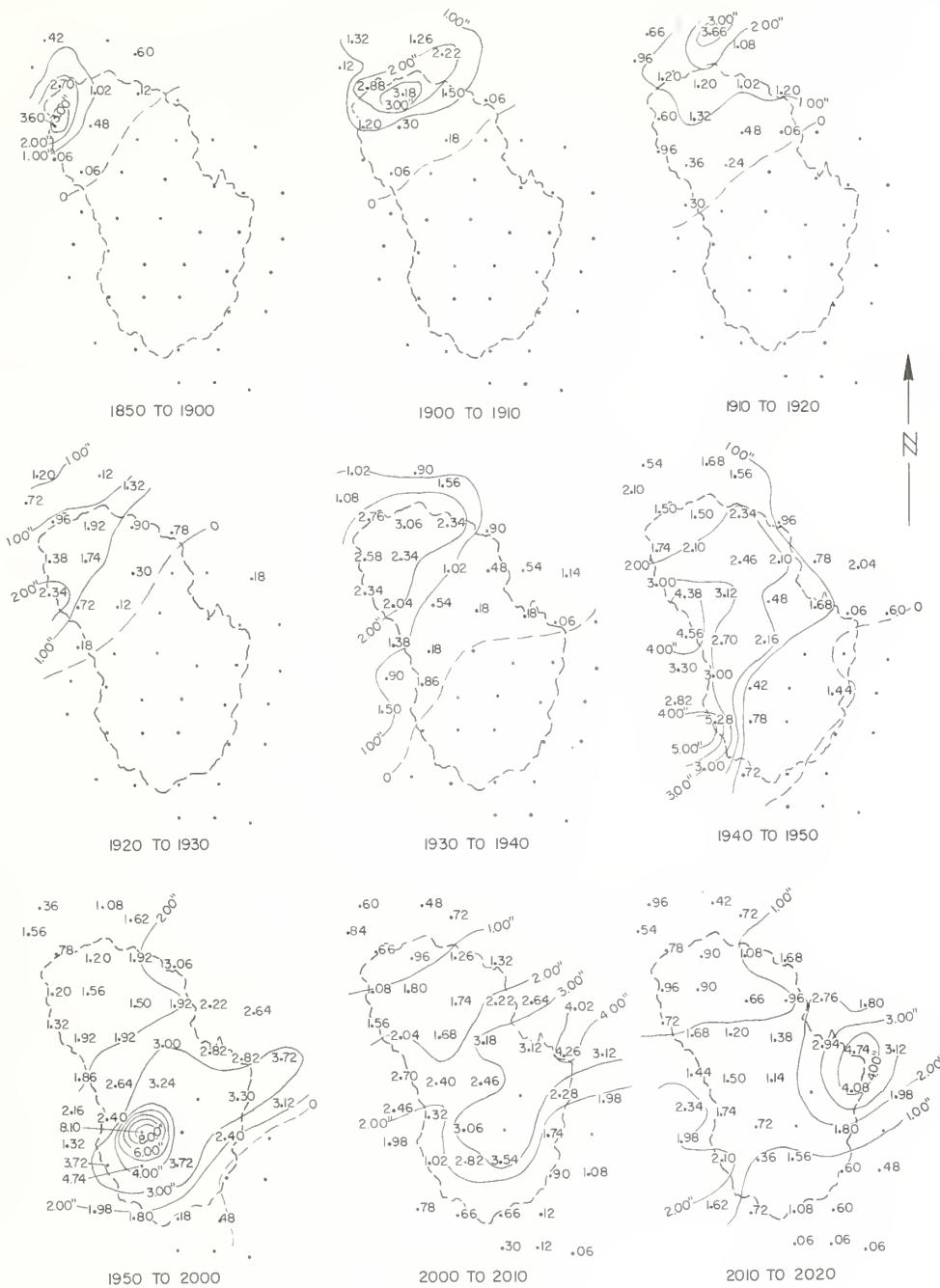


FIGURE 3-8.—Rainfall pattern from storm of September 20, 1965 at Sugar Creek watershed.

could be obtained from a network that is considerably less dense. However, when the same analysis was applied to subdrainage areas within the study reach, any reduction in the number of gages resulted in a poorer definition of the rainfall pattern and areal mean rainfall estimates.

The largest precipitation amounts recorded by the network occurred during a severe storm on September 20, 1965 in the northwest section of the study reach on Sugar Creek watershed (Hartman et al. 1967). This storm produced a maximum point rainfall of 8.77 inches in 5 hours. Approximately 10,000 acres of cropland and timberland along Sugar Creek and the Washita River flood plains were flooded. The pattern of rainfall from this storm (fig. 3-8) shows a uniform increase from the 2-inch isohyetal near Gracemont to an 8-inch value near Hinton. However, this storm was composed of several small, intense cells of rainfall traversing the watershed at speeds up to 30 miles per hour (Nicks 1971). Figure 3-9 shows the relative size and shape of several of these cells as depicted by isohyetal plotings. Such cellular structures appear to be characteristic of the frontal-type thunderstorms that occur in this climatic region. Storm data such as these recorded by the network have been used in new rainfall measurement technique studies.



10 MINUTE RAINFALL INTENSITY (INCHES PER HOUR)

FIGURE 3-9.—Cellular structure of rainfall during storm of September 20, 1965 at Sugar Creek watershed.

RADAR RAINFALL MEASUREMENT

Rain-gage network measurements have been compared to rainfall estimates made by weather radar (Kessler and Wilks 1968). Using the WSR-57 radar at the National Severe Storms Laboratory at Norman, Okla., McCallister et al. (1966) showed close agreement between a storm pattern measured by the network and that measured by radar technique. Wilson (1966) closely approximated existing radar rainfall estimates for all Oklahoma thunderstorms. Hudlow (1967) found that, despite large discrepancies between the amount of rainfall measured by the network and that measured by radar, the radar accurately located the rainfall. This finding was confirmed by correlating the occurrence of runoff from the affected area with the indicated rainfall.

DEPTH-AREA-DURATION RAINFALL MODEL

The results of a study of depth-area characteristics of Oklahoma rainstorms are presented in the following discussion. Data from 10 years of records collected from a 228-gage network operated by personnel at the Center were used to develop a computer optimized depth-area-duration rainfall model for areas up to 1,000 square miles and durations from 1 to 24 hours.

The criterion used for selecting storms was one that would fit the needs of most water-resource planners and designers. The criterion included

storms that produced surface runoff at 1 or more of the 18 runoff measuring stations in the sub-drainage basins shown in figure 3-1.

Using this criterion, 138 runoff-producing storms, ranging in amount from 1.00 to 8.77 inches and with durations of 0.5 to 24 hours, were selected. Table 3-5 summarizes the characteristics of the selected data set. Storms were ranked according to amount and were broken into 1.00-inch-class intervals. The rainfall duration at the maximum station, the month of occurrence, the average return period frequency for each class interval are listed.

A mathematical model was developed to relate storm-center rainfall depth to mean depth of rainfall over a given area (Nicks and Igo 1980). The basic criteria for the model were based on the observations that the depth of the mean precipitation decreased with distance and that the rate of reduction of the point amount increased with shorter duration of rainfall at the storm center.

The model used to calculate the mean rainfall covering given areas for a given duration is

$$P_A = P_p - \frac{P_p AD^m}{a + bA}, \quad (1)$$

where P_A is the mean rainfall depth in inches for area A in square miles; P_p is the storm-center point amount in inches; D is the duration of the storm-center rainfall in hours; and m , a , and b are regression parameters.

A nonlinear least squares optimization pro-

Table 3-5.—Characteristics of 138 storms used in depth-area-duration analysis

Class interval (in)	Number in class	Percentage, all storms	Range		Month of occurrence
			Return period ¹ (yr)	Duration (h)	
8.00-8.77	2	1	>100	5-14	September.
7.00-7.99	0	0	.....	.....	.....
6.00-6.99	3	2	73-93	2.5-10	May, August, September.
5.00-5.99	7	5	11->100	4-19	May, June, August, September.
4.00-4.99	9	7	4-75	2-20	April-June; September, October.
3.00-3.99	26	19	1-75	1-16	April-September.
2.00-2.99	68	49	1-13	0.5-24	April-December.
1.00-1.99	23	17	<1-5	0.5-24	January-May; July-October; December.

¹Source: Hershfield 1961.

cedure developed by DeCoursey and Snyder (1969) was used to fit data from the 138 storms to the model and thereby derive values for m , a , and b . The optimization procedure is based upon the method of differential corrections employing the multivariate technique of principle components analysis. Optimization of parameters a , b , and m ended with a multiple correlation of 0.88 and a standard error of estimate of 0.44 inch.

Results of the model are presented in graphical form in figure 3-10, which shows a family of depth-area curves constructed by evaluating the model at 1-, 6-, 12-, and 24-hour storm durations. The ordinate represents the ratio of area depth to storm-center depth as given by

$$R = 1.0 - \frac{AD^m}{a + bA}, \quad (2)$$

where R is the ratio of area rainfall depth (P_A) to the storm-center amount (P_p).

Individual comparisons of actual storm depth-area data used in the analysis were made. Further checks were made on the error of the model as

Table 3-6.—Mean error between observed and computed depths associated with given areas

Area (mi ²)	Error (per cent)
50	7.8
100	10.3
200	16.5
400	20.7
800	23.3
1,200	27.0

associated with given areas; these data are listed in table 3-6. The mean error for storms tested show a range of 7.8 to 27.0 percent for points along the curve, increasing from 50 to 1,200 square miles. From these data it appears that the mean error between computed and observed depths increases with area.

Additional tests of the model were made using storm isohyetal maps from published storm

(Continued on page 34.)

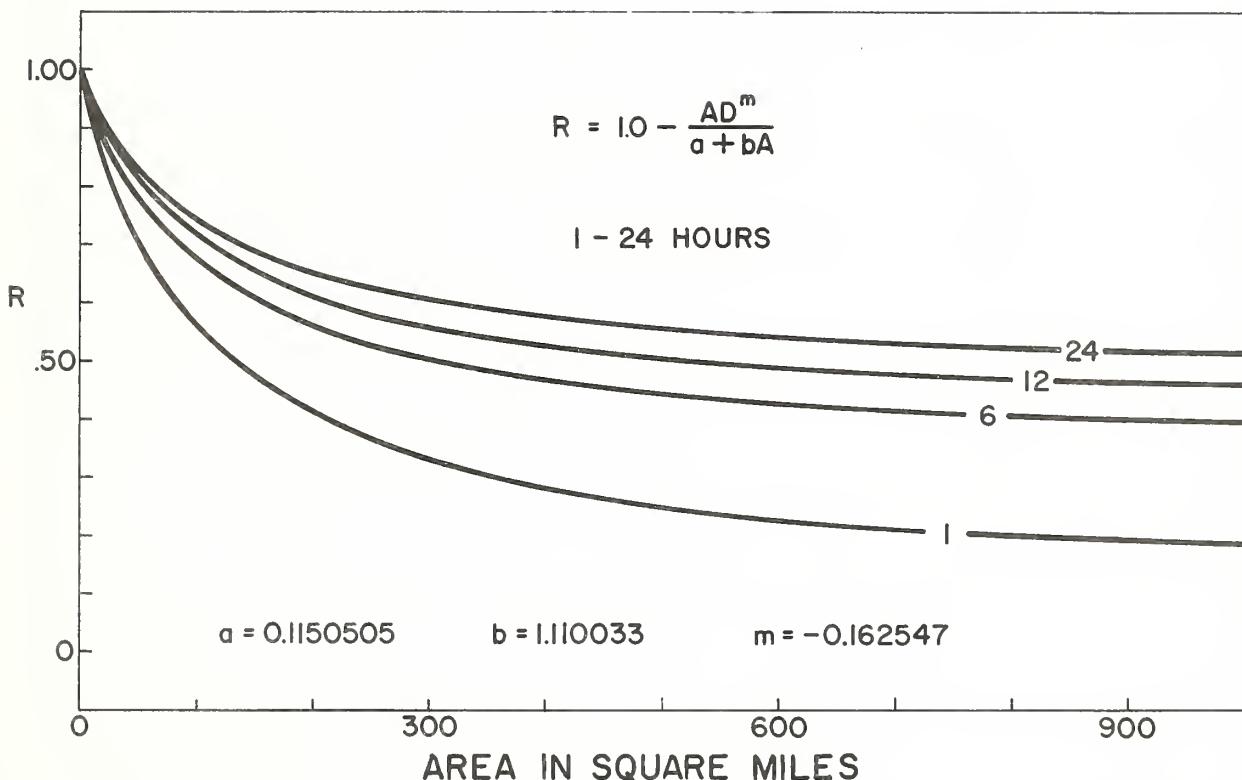


FIGURE 3-10.—Evaluation of depth-area-duration model as a ratio (R) of point to mean areal depth.

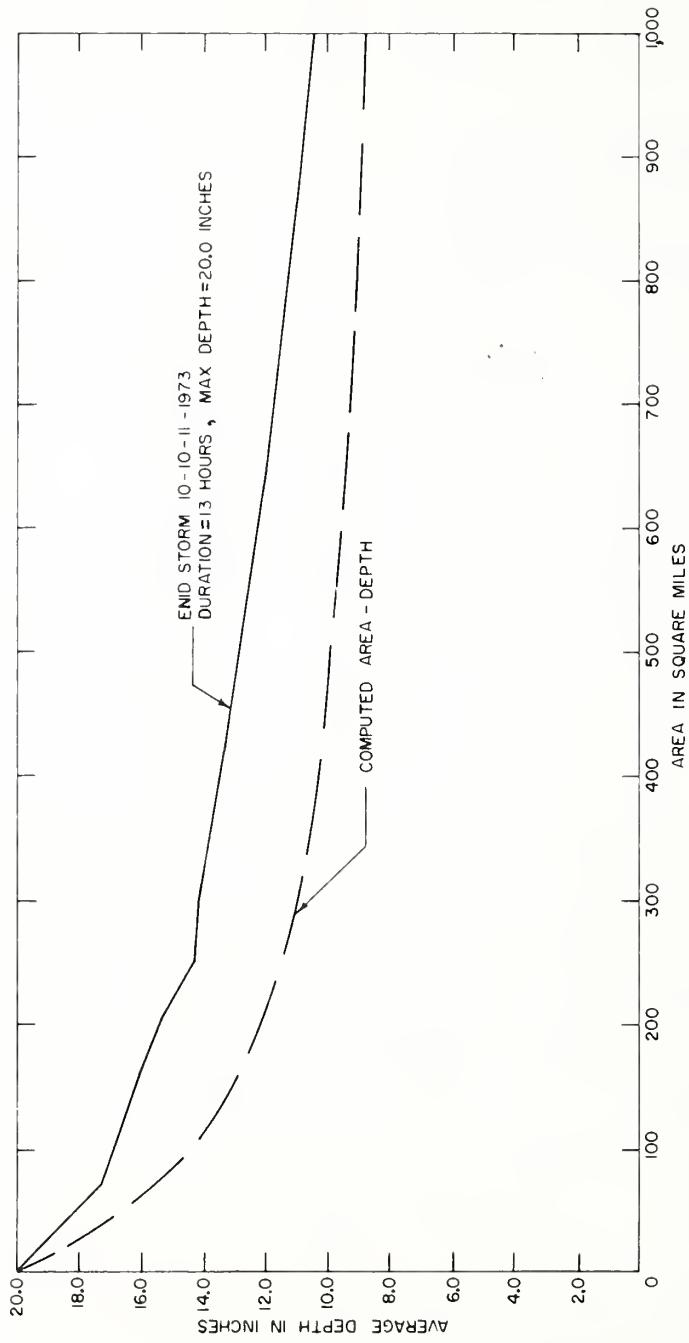


FIGURE 3-11.—Depth-area curve of total rainfall during storm centered at Enid, Okla., and simulated depth-area curve from model evaluated at 20-inch center rainfall depth and 13-hour duration.

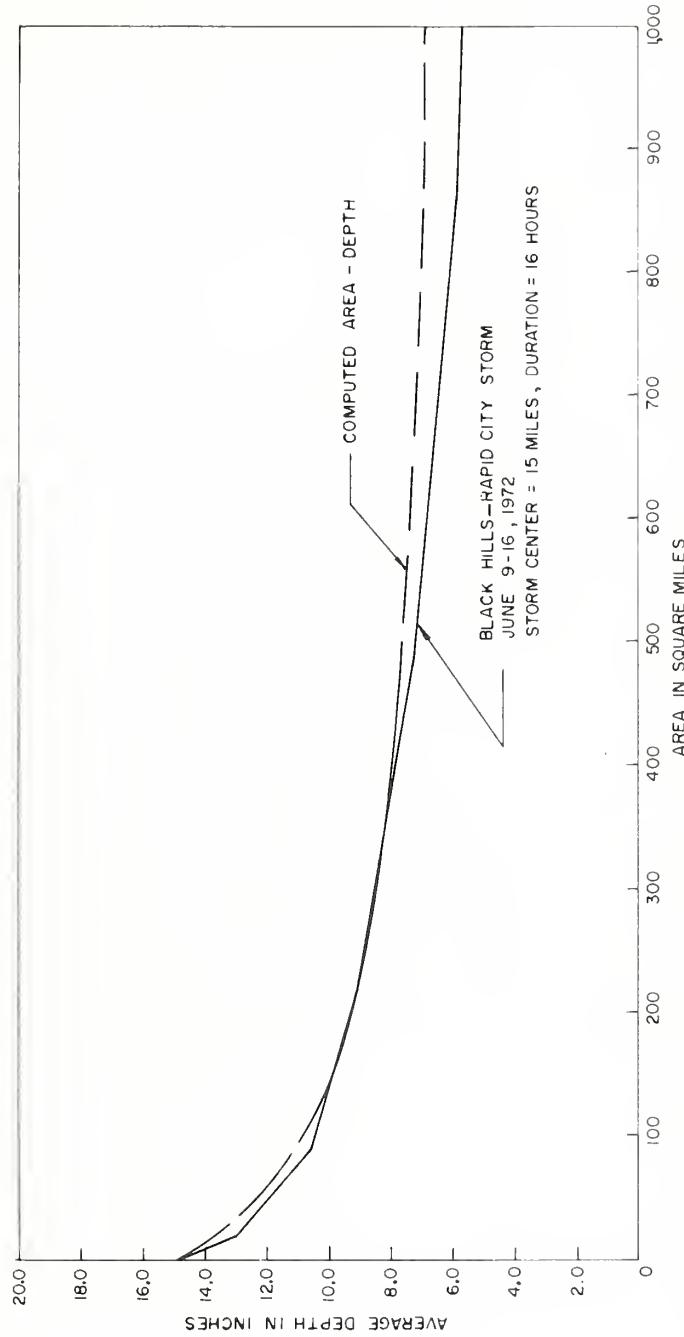


FIGURE 3-12.—Depth-area curve of total rainfall during Rapid City-Black Hills storm and simulated depth-area curve from model evaluated at 15-inch center rainfall depth and 16-hour duration.

reports. A convective storm system that developed over north and central Oklahoma was one such storm used in the tests. This devastating storm produced 20 inches of rainfall near its center at Enid and produced extensive flooding over five counties in north central Oklahoma, which resulted in six deaths and numerous injuries. Two reports were published on this storm, one dealing with the meteorological conditions that led to the storm's development and progress (Merrit et al. 1974) and another that describes the surface-water flooding resulting from the storm (Binghon et al. 1974). Both reports contain isohyetal maps of the storm. These maps were analyzed, and a depth-area curve of total storm rainfall was prepared for testing with the model.

A storm depth of 20 inches and storm duration of 13 hours were used to simulate the depth-area curves, using the model in the form given in equation 2. The resulting simulated depth-area curves and the actual curve developed from the isohyetal maps can be compared from figure 3-11. This shows the simulation of the depth-area curve from the model evaluation to underestimate the actual depth by a maximum error of 23 percent at 300 square miles. This error is within the error determined from network data tested with the model.

The second storm tested by the model was the Rapid City-Black Hills storm of June 1972 (Schwarz et al. 1975). The storm report describes this storm as producing nearly 15 inches of rainfall in 6 hours, causing extensive flooding over a large area of South Dakota approximately 40 miles long and 20 miles wide. The report also gives a isohyetal map showing a total storm maximum amount of 15 inches and a duration of rainfall over the flooded area of 16 hours. A depth-area curve was developed using the map, and simulation of this curve was computed using equation 2. The resulting curves can be compared from figure 3-12.

The simulation of the Rapid City storm compares closely with the observed depth-area curve developed from the isohyetal map. Maximum error between observed and simulated depths was 17 percent at 1,000 square miles, indicating a rather close fit throughout the range of areas shown.

Additional testing of the model was done using data from a network of gages in the Chicago, Ill., urban area. Data supplied by the National

Weather Service were fitted to the model in the form given in equation 2. These data consisted of 203 storms over a 25-year period, from 1947 to 1972. Essentially, the same constants for parameters a , b , and m resulted from the nonlinear least squares optimization of these data. A comparison of curves developed from the Chickasha and Chicago data can be made from figure 3-13. For all practical purposes, the two models with optimized parameters are the same.

STORM SEVERITY INDEX

A storm severity index was developed using breakpoint rainfall-intensity data from several selected gages of the network (A. D. Nicks and G. A. Gander, unpublished data). The objective of this study was to develop a method of ranking thunderstorm amount, duration, and intensity distribution within a storm to the runoff potential of the storm itself. Of particular importance were the intensity of rainfall, its occurrence within the storm duration, and the duration of the storm. These characteristics, coupled with the infiltration characteristics of the soil, were used to develop an index of runoff potential for each storm having a total accumulation of 0.10 inch or greater.

The index was developed as follows. First, the storm intensities were made dimensionless by dividing the rainfall amount for the intensity breakpoint by the total storm amount and accumulating these values to 100 percent. The durations for each breakpoint were also converted to an accumulated percentage. The results of these conversions when plotted gave a dimensionless representation of the accumulated rainfall trace of the storm at a gage; an example of this plotting is shown in figure 3-14. Also shown in this illustration is the plotting of the total accumulated infiltration from the storm as represented by the Philip (1957) infiltration equation

$$F = St^{0.5} + At, \quad (3)$$

in which F is the total infiltration, t is the time from the beginning of the storm, and A and S are constants related to the soil type and cover. The soil constants used in this study were those for a silt loam soil that represents the rangeland soils

of the Reddish Prairie land resource area. Other soil parameters could have been used; however, the values selected had been determined from numerous field tests with a double-ring infiltrometer.

The severity index was determined by calculating the duration for which the rainfall curve exceeded the infiltration curve shown in figure 3-14. The infiltration equation was solved for the duration it would take for the entire storm rainfall volume to infiltrate. Next, this duration was divided by the excess rainfall duration to provide the index value. Storm severity indices such as

the one described above were calculated for each storm during which rainfall was recorded.

Index values greater than 0.50 were ranked and their corresponding frequency calculated; a plotting of these frequencies is shown in figure 3-15. This method of indexing storms was applied to 13 rain-gage records at Chickasha. The period of record used was 16 years. A longer record was available for breakpoint rainfall at Guthrie, Okla. (1937-56), located approximately 60 miles north of the network. The results of the index frequency calculated for the Guthrie record are shown in figure 3-16. The two frequency curves are ap-

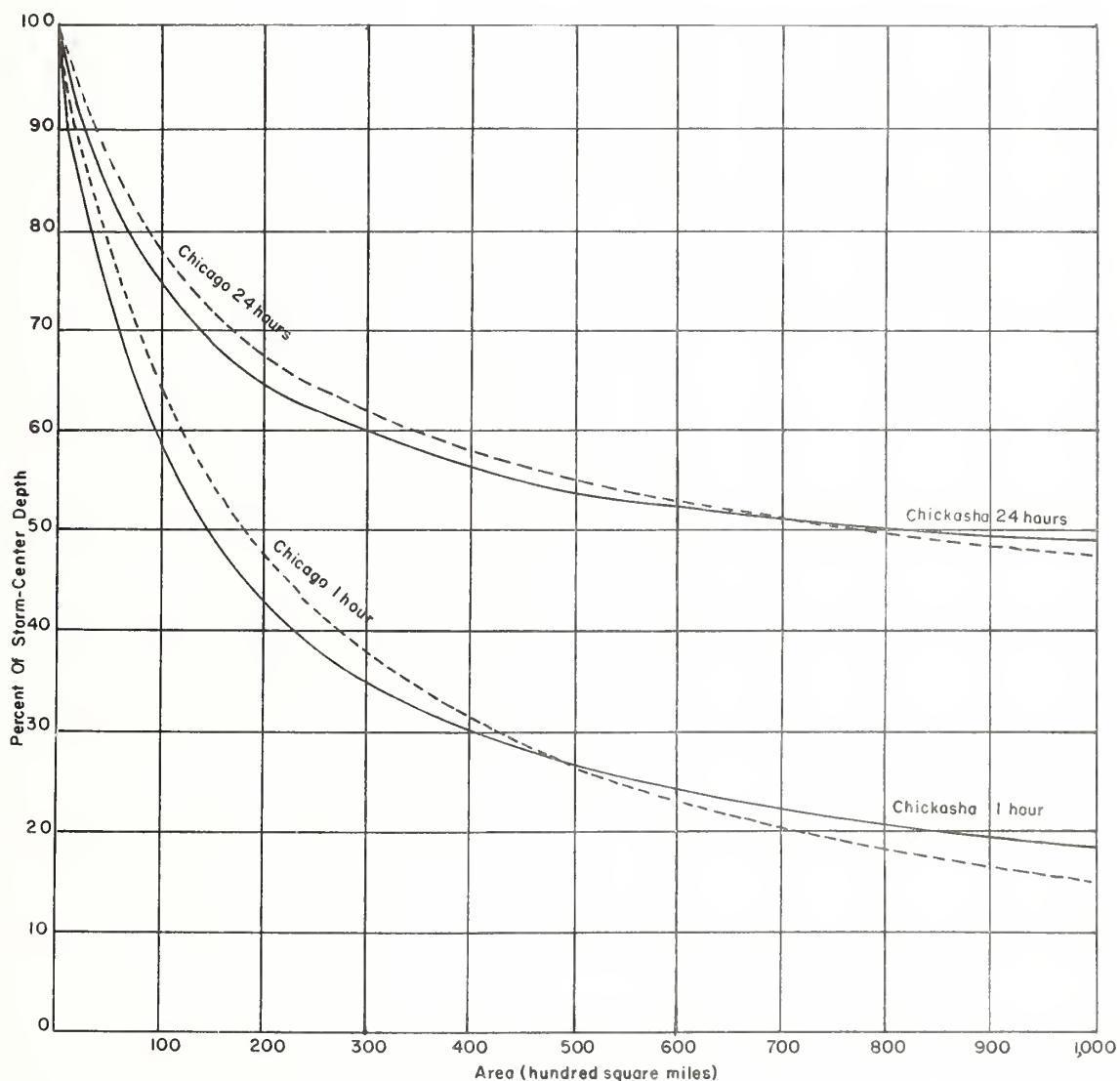


FIGURE 3-13.—Simulated depth-area curves representing models evaluated at 1- and 24-hour storm durations from Chickasha and Chicago gage-network data.

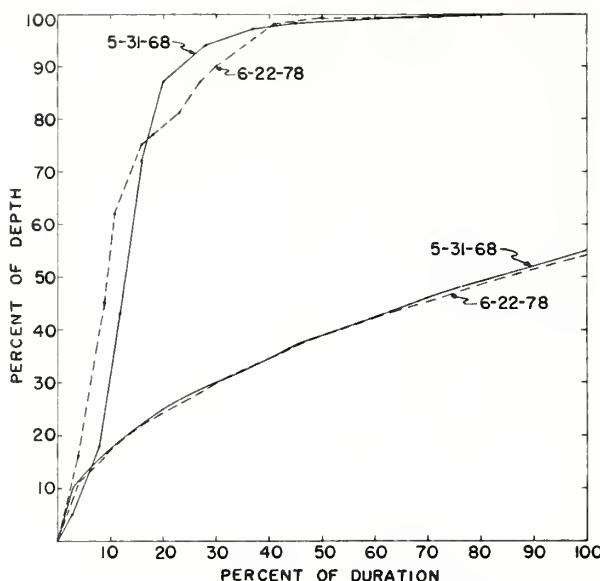


FIGURE 3-14.—Accumulated rainfall curves (upper) and infiltration curves (lower) for calculating storm severity index.

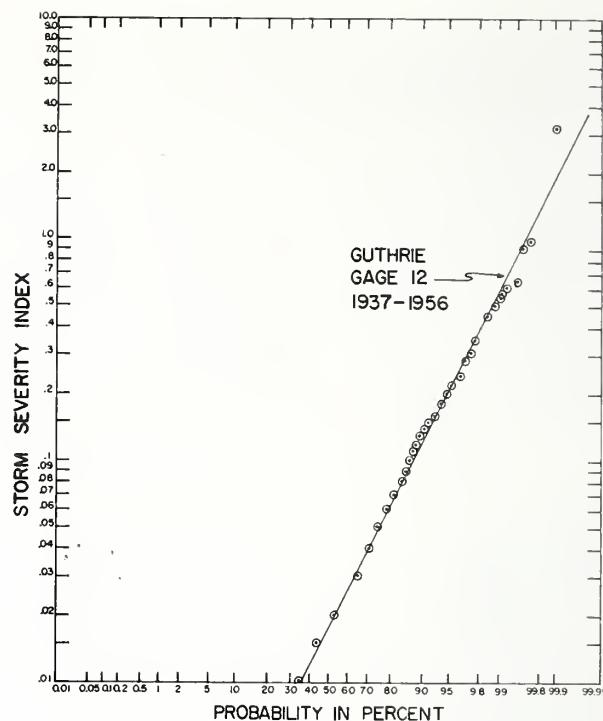


FIGURE 3-16.—Frequency curve of storm severity index for gage 12, Guthrie, Okla., 1937-56.

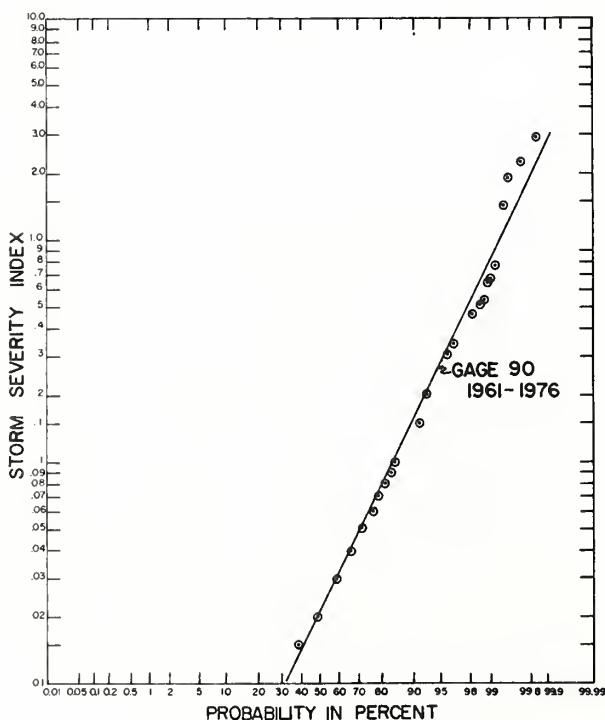


FIGURE 3-15.—Frequency curve of storm severity index for gage 90, Chickasha, Okla., 1961-76.

proximately the same. Table 3-7 lists the gages from the network at Chickasha for which indices were calculated. Also listed in table 3-7 is the quartile of storm duration in which the most intense portion of the rainfall fell, the total number of storms, and an average index value for each quartile.

Table 3-8 lists a summary of the most severe storms, those with an index value greater than or equal to 0.50. From these data and the frequency plots, we conclude that the most intense portion of a storm usually falls within the first 25 percent of the storm duration and that the most severe storms follow this pattern.

The frequency curves show that a storm with an index of 3 would occur in 1 of 500 storms and that an upper limit might be less than 10. An example of a severe storm that supports this assertion is shown in figure 3-17, which represents a storm that occurred at Enid, Okla., on October 10-11, 1973. The total storm amount exceeded 15 inches, with a duration of approximately 14 hours. The index calculated for this storm was 8.51.

The type of index illustrated in this study could be useful to planners and engineers in helping to

Table 3-7.—Quartile of storm duration in which greatest intensity occurred, total number of storms recorded at each gage, and average index value for each quartile, Chickasha, Okla., 1961-78

Gage No.	No. storms having greatest intensity in quartile—				Total No. storms with index > 0.50
	1	2	3	4	
10	306	105	92	82	585
40	262	97	87	87	533
46	318	110	91	75	594
68	247	123	98	92	560
90	327	119	109	103	658
107	260	118	87	67	532
125	298	119	97	88	602
126	278	123	102	84	587
128	292	117	94	95	598
147	245	117	83	87	532
155	261	108	102	82	553
162	282	113	93	103	591
Total	3,623	1,486	1,227	1,113	7,469
Percent, all storms	48	20	16	15	.....
Avg. index value	0.07	0.05	0.08	0.03	.....

Table 3-8.—Distribution of storm severity index by quartile of storm duration for storms having index values greater than or equal to 0.50

	Quartile			
	1	2	3	4
Number storms	65	31	11	5
Percent, all storms	58	28	10	4
Average index value	0.77	1.00	0.81	0.90

determine the size of storms or the storm characteristics of a climatic region that would exceed design criteria. It also illustrates that severe storms can occur that far exceed the protection afforded by normal conservation and management practices.

When the results of this study are compared with other studies of rainfall duration-intensity distribution, there are differences that warrant further consideration. For instance, Kent (1968) found from a study of rainfall distribution over the United States that the most intense portion of rainfall occurred near the end of the storm duration. However, this study supports the fact that the most intense rainfall in Oklahoma occurs in the first part of the storm duration and that the majority of severe runoff storms there have this characteristic.

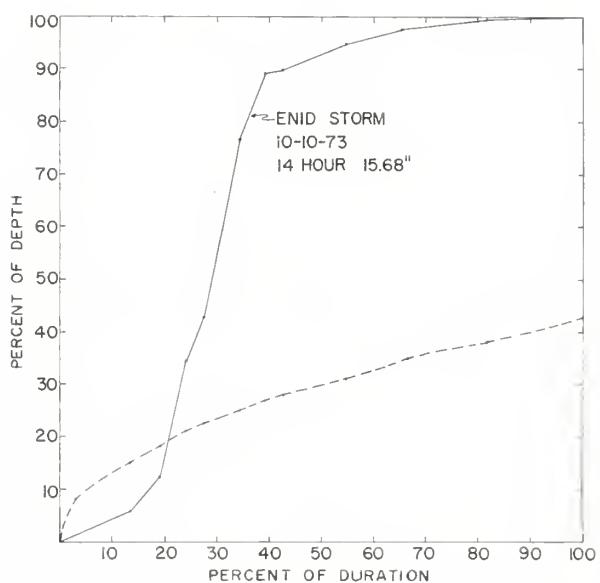


FIGURE 3-17.—Accumulated rainfall curve (upper) and infiltration curve (lower) for calculating storm severity index, storm of October 10-11, 1973 at Enid, Okla.

STOCHASTIC CHARACTERISTICS

Stochastic characteristics of rainfall for the network area have been studied. Nicks (1974), in a study to develop a method for synthetically generating patterns of rainfall over a large area such as the network, considered maximum daily rainfall amounts, occurrence of daily maximums in space, sequence of wet- and dry-day periods, and size and shape of rainfall patterns. To synthetically construct patterns of daily rainfall, a four-phase generating system was developed that utilized the rainfall characteristics of a 9-year historical record (1962-70). Each phase of the generating sequence is shown in figure 3-18. In this sequence, each phase is related to the preceding one. The pattern of rainfall is dependent on the maximum amount recorded, which in turn is influenced by the position of the storm with respect to the network. Finally, all of the phases are dependent on the sequence of rainfall events occurring on or near the network.

Starting with the occurrence of a wet or dry day, the location of the center amount and pattern of daily rainfall are generated by randomly sampling statistical distributions developed to represent each of these characteristics. The method used to generate the number and distribution of events on the watershed was a two-state Markov chain, which has been used with success by other investigators. It proved to be an appropriate method to use because tests of the wet- or dry-day occurrences showed no significant difference in observed data.

There were very few references in the literature that gave any description of how the spatial distribution of storm centers should be made. The spatial distribution of storm systems was assumed to be random. If this assumption was correct, then stations of the network should have an equal chance of recording the maximum storm amounts over a long period of time. The sampling of many storm systems by a network should result in a uniform, random distribution of maximum amounts.

Figure 3-19 shows the distribution of maximum daily rainfall occurrences at each station during the historical record (1962-77). The number of occurrences ranged from a high of 74 at the extreme northwest gage to 3 near the center of the network. In general, the largest number of maximums occurred on or near the

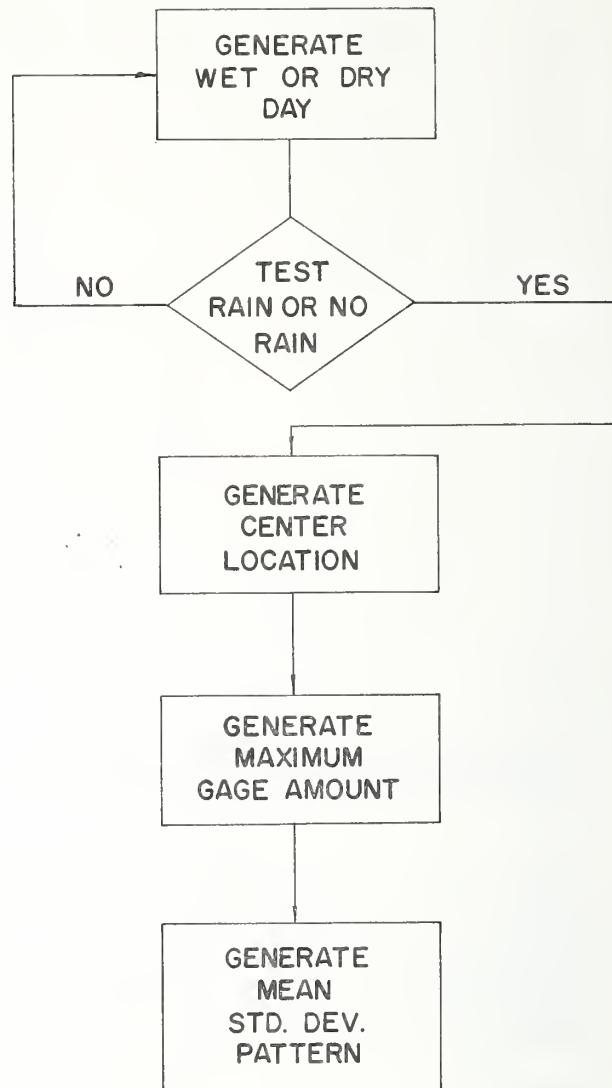


FIGURE 3-18.—Flow chart of rainfall-generation model.

boundary of the network. The large values at these stations are attributed to storms that were centered off the network and yet were close enough so that their patterns extended to just a few gages near the boundary. In most cases, the maximums in the interior of the network were considered to be uniformly distributed. Tests made on generated data indicated that this assumption of uniformity was valid.

Daily rainfall amounts have been fitted to many types of frequency distributions. The best fit for maximum daily rainfall on the network was a skewed normal distribution of the form

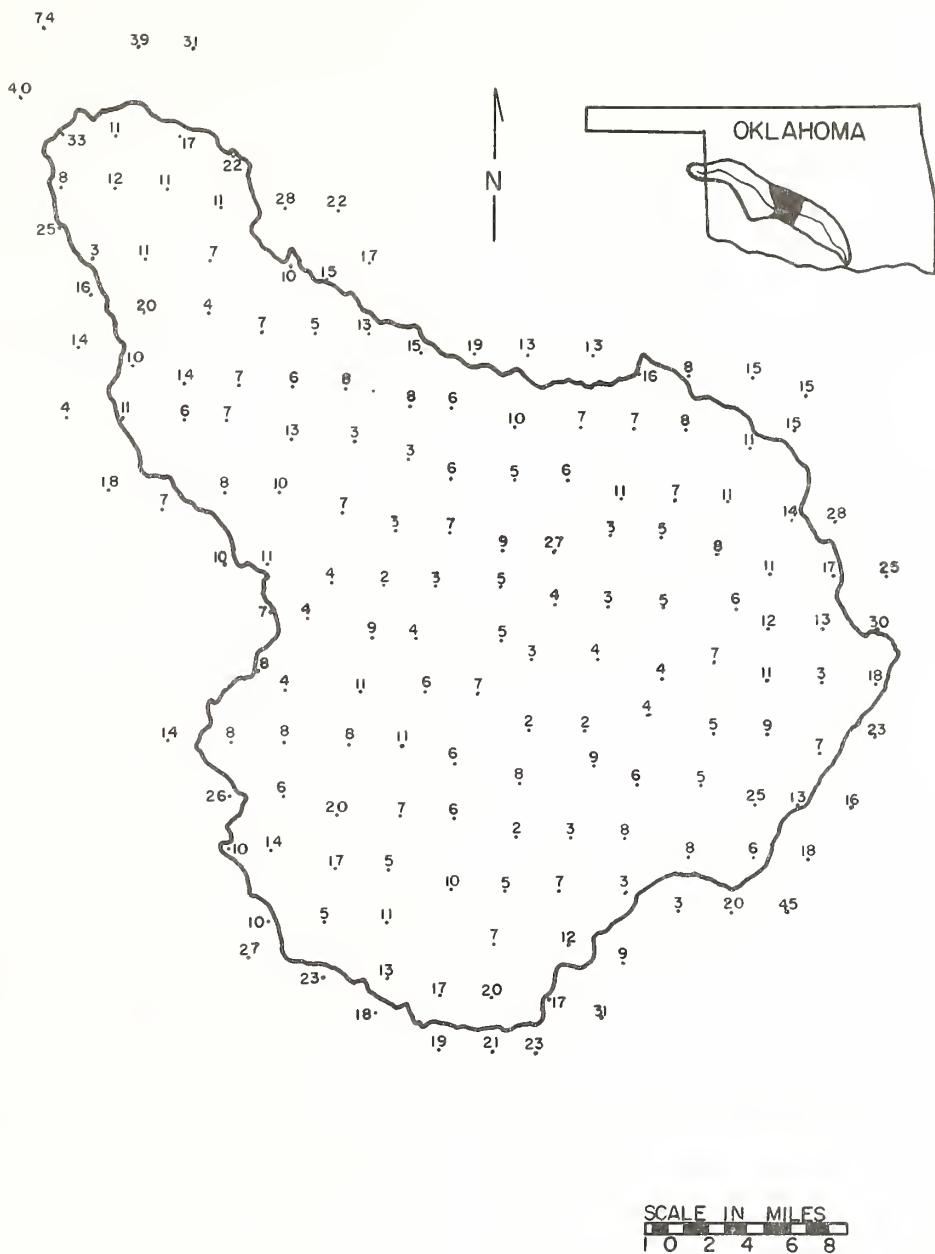


FIGURE 3-19.—Number of maximum daily rainfall occurrences at each of 168 rain-gage stations, 1962-77.

$$x = \frac{6}{g} \left\{ \left[\frac{g}{2} \left(\frac{X-u}{s} \right) + 1 \right]^{0.33} - 1 \right\} + \frac{g}{6}, \quad (4)$$

where x is the skewed normal variate; X is the

raw variate; and u , s , and g are the mean, standard deviation, and skew coefficient of the raw variate. An example of this distribution fitted to maximum daily rainfall on the network during 1 month (September) is shown in figure 3-20.

Rainfall depths at stations of the network were

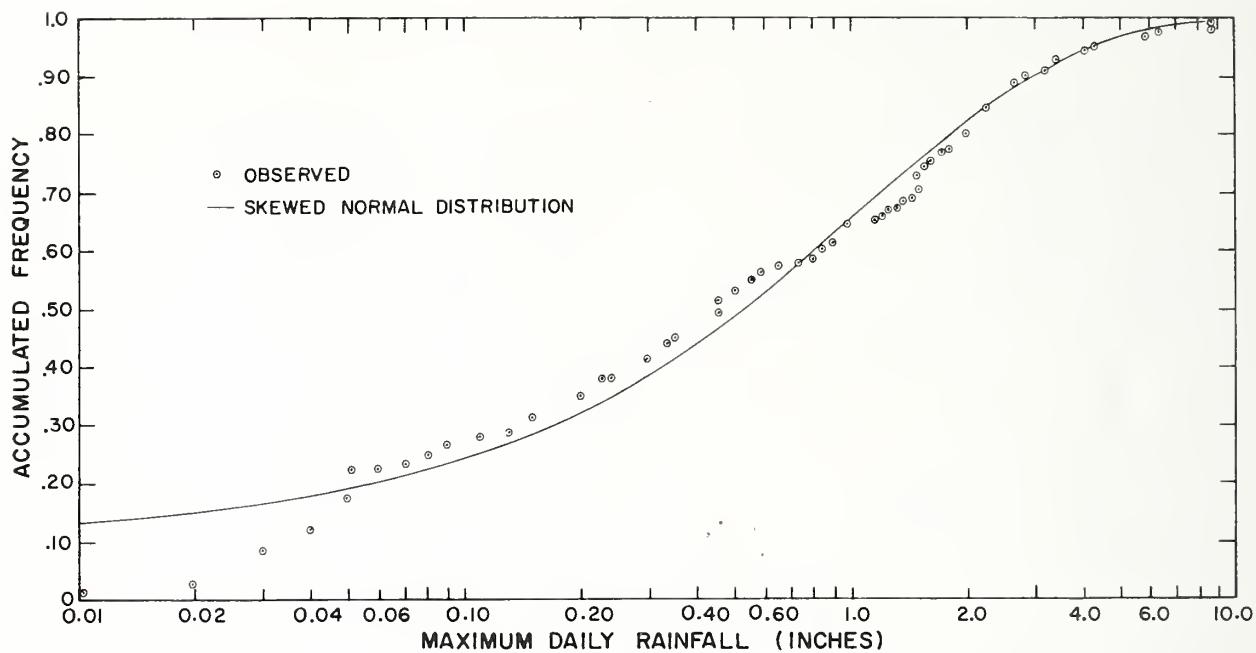


FIGURE 3-20.—Maximum daily rainfall on the network during 1 month fitted to skewed normal distribution.

generated using the deterministic and probabilistic model

$$P_j = P_{\max} r_j + s z \sqrt{1 - r_j^2}, \quad (5)$$

where P_j is the rainfall amount at station j , P_{\max} is the maximum rainfall, s is the standard deviation of storm rainfall, r_j is the reduction factor for station j , and z is the standard normal deviate. The reduction factor was estimated by calculating the interstation correlation between P_{\max} and P_j .

The four-phase system for generating the pattern of daily rainfall was tested by generating 10 sequential synthetic runs of 10-year length. These data were compared with observed records from the network. These tests showed that 71 percent of the synthetic records at 168 stations would be accepted as being from the same population of observed records. A Markov chain model for generating a wet day-dry day sequence for the network area was highly satisfactory, as was the method of generating mean rainfall for the area. Further refinement of the method of generating the rainfall pattern is needed.

The generation of synthetic data was extended by Nicks (1975) and Nicks and Harp (1980) to include the generation of synthetic air temperature, solar radiation, and potential evapotranspiration. The objective of this study was to generate the inputs required by hydrologic models so that records longer than those provided by historical data could be used with these models to develop planning data on a long-term scale.

A method was developed for generating daily air-temperature and solar-radiation values. These data meet the requirement for those models that require these two variables, such as the Stanford and Streamflow Synthesis and Reservoir Regulation (SSARR) models. The combination of these two values, when used with a potential evapotranspiration model, meet the requirements of hydrologic models that require daily or monthly evaporation input.

The model proposed for stochastically generating daily air-temperature data is similar to the streamflow simulation model given by Fiering (1967). The model for temperature is

$$T_i = \bar{T} + r_T (T_{i-1} - \bar{T}) + t \sigma_T \sqrt{1 - r_T^2}, \quad (6)$$

where T_i is the current day's temperature ($^{\circ}\text{F}$); T_{i-1} is the previous day's temperature ($^{\circ}\text{F}$); \bar{T} is the mean daily temperature ($^{\circ}\text{F}$); r_T is the lag 1 correlation; σ_T is the standard deviation of daily temperature; and t is a standardized random, normal, independently distributed variate.

Mean daily temperature and maximum and minimum temperatures could be generated with the above equation. However, in order to generate representative air-temperature data, it is necessary to relate the synthetic temperatures to the sequence of rain or no-rain days. To achieve this relation, four equations were developed that correspond to the four rain-state conditions that could exist. These are (1) a dry day following a dry day, (2) a dry day following a wet day, (3) a wet day following a dry day, and (4) a wet day following a wet day. To provide a transition between seasons, models were developed for each month of the year. Finally, it was considered desirable to generate both maximum and minimum daily temperature, thus another subscript was added to the model. Equation 6 was modified to

$$T_i(K,M,N) = \bar{T}(K,M,N) + [T_{i-1}(K,M,N) - \bar{T}(K,M,N)] \\ r_T(K,M,N) + t\sigma_T(K,M,N) \sqrt{1 - r_T^2(K,M,N)}, \quad (7)$$

in which $K=1, 2, 3$, or 4 , the four possible rain-state conditions; $M=1, 2, \dots, 12$, the number of months or seasons; and $N=1$ or 2 , representing maximum and minimum temperatures, respectively.

The model to generate daily total solar radiation is similar to the one developed for daily temperature. The general model is

$$S_i = \bar{S} + r_s(S_{i-1} - \bar{S}) + t\sigma_s \sqrt{1 - r_s^2}, \quad (8)$$

where S_i is the total radiation on day i in langleys, S_{i-1} is the total radiation on the previous day in langleys, \bar{S} is the mean daily solar radiation in langleys, r_s is the lag 1 correlation coefficient, σ_s is the standard deviation of daily radiation, and t is a standardized normal, random variate.

Equation 8 was modified in much the same way as the temperature model to provide generation of monthly or seasonal transition data and to relate the solar radiation values to daily rain conditions. The modified model is given as

$$S_i(K,M) = \bar{S}(K,M) + r_s(K,M) [S_{i-1}(K,M) - \bar{S}(K,M)] \\ + t\sigma_s(K,M) \sqrt{1 - r_s(K,M)^2}, \quad (9)$$

where $K=1, 2, 3$, or 4 , the four possible rain-state conditions, and $M=1, 2, \dots, 12$, the months of the year.

To generate the sequence of rain days required by equations 7 and 9, a two-state Markov chain model was selected. This model has been used successfully to generate sequences of rain events in Oklahoma (Nicks 1974). The use of the model appears to be well justified, considering its accepted use in various climates.

This method involves the calculation of two conditional probabilities: α , the probability of a wet day following a dry day, and β , the probability of a dry day following a wet day. The two-state Markov chain for the combination of conditional probabilities is

		Future state	
		Dry	Wet
		Dry	$1-\alpha$
Present state	Dry	α	
	Wet	β	$1-\beta$

Rainfall sequences, i.e., wet- and dry-day occurrences, can be generated throughout the year with seasonal transition, as required in equations 7 and 9. Conditional probabilities α and β were

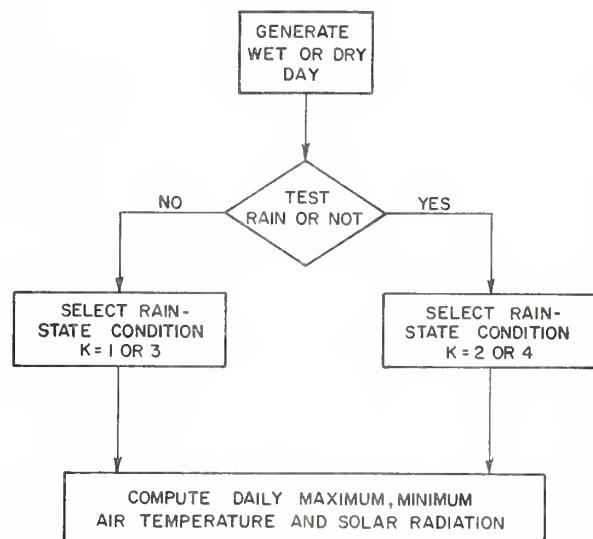


FIGURE 3-21.—Flow chart of air-temperature and solar-radiation generating model.

Table 3-9.—Monthly air-temperature mean (\bar{T}), standard deviation (σ), and lag 1 correlation coefficient (r) for the four rain-state conditions

Month	State																							
	1 Dry-Dry				2 Dry-Med				3 Wet-Dry				4 Wet-Wet											
	Maximum		Minimum		Maximum		Minimum		Maximum		Minimum		Maximum		Minimum									
	\bar{T}	σ	r	\bar{T}	σ	r	\bar{T}	σ	r	\bar{T}	σ	r	\bar{T}	σ	r									
1	49.0	13.3	.666	24.5	9.9	.698	46.8	14.2	.749	30.5	11.9	.537	40.8	15.7	.586	23.2	12.6	.910	48.3	14.6	.431	35.3	12.1	.648
2	55.2	11.0	.399	28.0	8.0	.413	50.5	11.4	.350	31.8	8.3	.217	48.6	10.2	.560	27.8	9.0	.838	45.1	10.8	.518	32.0	9.7	.522
3	63.6	13.1	.583	36.6	10.3	.604	61.2	14.1	.792	42.4	10.2	.675	60.2	11.9	.452	36.8	8.8	.743	58.2	12.5	.779	41.9	9.4	.753
4	75.7	9.8	.478	47.7	10.7	.599	72.7	11.0	.537	54.3	8.0	.582	73.6	9.5	.489	49.2	9.5	.801	69.6	8.5	.555	52.1	6.7	.413
5	83.5	7.5	.610	57.3	8.0	.720	79.4	8.5	.605	58.7	6.9	.596	78.3	7.5	.406	54.3	8.3	.743	74.9	8.4	.297	58.2	5.2	.531
6	91.2	5.1	.735	67.4	5.8	.757	88.4	6.5	.352	67.1	4.2	.175	88.0	6.3	.765	66.0	5.7	.709	82.6	7.6	.394	65.0	4.2	.703
7	95.3	5.3	.765	71.3	5.4	.769	92.3	6.7	.503	71.7	3.6	.584	92.3	6.7	.633	70.2	4.7	.800	89.9	6.7	.521	70.6	3.9	.476
8	93.7	5.4	.784	68.9	5.7	.785	91.3	6.4	.636	69.0	3.6	.535	90.1	4.3	.575	67.5	4.9	.648	85.8	6.5	.299	68.2	3.8	.581
9	85.3	7.5	.787	62.2	7.6	.839	82.5	9.7	.536	63.8	7.6	.614	82.8	8.6	.761	61.1	9.2	.877	78.1	9.6	.521	62.5	6.7	.544
10	77.0	8.8	.704	49.7	9.4	.757	72.1	11.0	.660	52.8	7.8	.300	68.6	10.8	.438	48.2	8.4	.854	61.3	9.0	.443	47.4	6.7	.647
11	63.6	11.4	.640	38.0	10.1	.696	59.5	12.2	.867	42.9	8.9	.481	57.2	10.3	.566	36.3	8.0	.847	52.0	8.2	.565	40.1	7.3	.594
12	52.6	11.6	.619	28.7	8.1	.572	51.2	14.3	.815	34.0	10.8	.589	47.1	12.6	.593	28.1	9.5	.528	44.7	13.1	.737	31.7	8.5	.659

Table 3-10.—Monthly solar radiation mean (\bar{S}), standard deviation (σ), and lag 1 correlation coefficient (r) for the four rain-state conditions¹

Month	Rain-state condition											
	1, Dry-dry			2, Dry-wet			3, Wet-dry			4, Wet-wet		
	\bar{S}	σ	r	\bar{S}	σ	r	\bar{S}	σ	r	\bar{S}	σ	r
January	250.1	85.2	0.415	194.2	99.6	-0.017	90.0	61.0	-0.022	68.4	43.0	0.128
February	324.6	100.2	.218	308.3	120.0	.043	164.5	130.7	.300	144.0	116.0	.171
March	421.1	127.6	.225	337.5	172.0	.140	273.7	162.4	.368	169.7	123.5	.197
April	520.8	129.9	.270	459.9	155.1	.152	339.8	179.7	.122	246.8	148.6	.163
May	597.0	103.9	.402	511.9	161.8	.265	383.0	106.4	.080	377.0	169.7	.174
June	616.4	89.8	.391	573.5	103.3	.270	444.6	153.0	-.045	415.8	137.6	.054
July	594.7	98.6	.333	571.5	106.6	.414	452.5	122.6	.224	415.9	131.1	.013
August	561.5	88.3	.321	530.7	84.0	.301	436.5	132.1	.178	411.2	152.8	.242
September	460.3	103.2	.588	431.7	95.9	.164	323.9	137.8	.250	266.4	146.4	.332
October	368.4	104.2	.314	343.2	106.1	.087	183.8	125.1	.185	209.7	116.7	.168
November	265.3	84.5	.346	257.0	87.7	-.123	131.2	113.8	.407	118.4	123.7	.121
December	222.8	82.7	.256	184.3	83.7	.172	102.1	78.7	.206	84.3	72.1	.039

¹From data recorded and published at Oklahoma City Airport Weather Bureau Station.

calculated for each month of the year. Then sequences of wet and dry days were determined by alternately generating uniform random numbers between zero and 1 and testing against the seasonal value of α and β .

Generation of synthetic daily temperatures with an equation consists of generating a uniform random variate to select one of the four rain-day conditions. Using the condition code for the given day, the appropriate monthly mean and standard deviation for maximum and minimum temperature are then selected. Next, another standardized random, normal variate is generated, and the daily temperature is calculated using equation 7.

Solar-radiation values are generated in nearly the same way as temperature. Once the rain-state condition is selected for the temperature calculation, another standardized random, normal variate is selected, and equation 9 is used to calculate the daily radiation value. A flow chart showing the general scheme for both general temperature and solar radiation is given in figure 3-21.

The necessary statistical parameters—mean, standard deviation, and lag 1 correlation coefficient—were calculated using data from the Oklahoma South Central Research Station near Chickasha. These data consisted of 11 years of air-temperature and rainfall data. Solar radiation for the same 11-year period at the Oklahoma City Airport category 1 weather station was used for the radiation parameter determination. The sta-

Table 3-11.—Conditional probabilities (α and β) computed from daily rainfall data recorded at South Central Research Station, Chickasha, Okla.

Month	β^1	α^2
January	0.519	0.093
February . . . . .	.588	.165
March . . . . .	.639	.171
April . . . . .	.542	.222
May . . . . .	.455	.216
June . . . . .	.524	.244
July . . . . .	.531	.214
August . . . . .	.481	.292
September . . . . .	.521	.294
October . . . . .	.532	.118
November . . . . .	.559	.122
December . . . . .	.667	.125

¹Probability of a dry day following a wet day.

²Probability of a wet day following a dry day.

tistical parameters for temperature, solar radiation, and rainfall wet day-dry day conditional probabilities are given in tables 3-9-3-11.

The models for daily maximum and minimum air temperature and solar radiation were programmed for digital computer processing, and synthetic data-generating runs were made. Using these generated data, tests were made for the adequacy of each model to mimic the actual data.

The meteorological data-generating systems described above should not be considered as

replacements for observation but rather as supplements to existing records. These systems do not provide an extension to existing records but do provide a method of determining the variation that exists in the historical observations. That is, if an evaluation of a watershed or basin were required using a given hydrologic model and only a short period of historical input data were available, then one might use synthetic records such as these to simulate sequences of hydrologic events that are different from the observed data. Wet and dry periods and extreme values, as well as means, would be present in the synthetic data, yet in a different order of occurrence. Even long records might be generated from short historical records such as those used in this study if the user is careful to construct the records by generating synthetic data for intervals not to exceed the historical record length.

Meteorological data-generating models capable of stochastically generating daily maximum and minimum temperature and total solar radiation were developed. A Markov chain model for generating the wet day-dry day sequences necessary to calculate daily rain conditions was tested and found to perform satisfactorily. Data generated from these models were tested against historical records and found to be adequate, representing the observed data in 11 of the 12 months of the year. Mean daily temperature calculated from the maximum and minimum synthetic temperature data was not significantly different from mean daily air temperature calculated from observed data. A further test of the data showed monthly evapotranspiration calculated using the Jensen model and synthetic daily temperature and solar radiation to be statistically the same as mean monthly evapotranspiration calculated from historical data.

SUMMARY

After nearly 18 years of operating the Washita River basin rain-gage network, personnel at the Center could summarize the results of many of the research studies by listing the many varied uses and applications of the data collected from the facility. The network was originally planned to provide the hydrologic inputs to the river basin study reach research programs. However, the data collected provided opportunities to make

other related studies not covered in the original objectives.

These data were used to develop new techniques for measuring rainfall for severe storm detection and flood forecasting. Research results from these studies have been used to design better radar equipment and techniques to monitor storm rainfall.

Variability of rainfall was defined using monthly and annual totals as well as storm-pattern totals. Annual variations were greater than expected from long-term climatic stations, showing an average variation of 14 inches within 29 miles during each year. These variations, often within a county area, are significant when compared with data used to forecast crop yield and production, which are generally based on one value of rainfall per county. Storm variations that show the cellular structure of storms producing larger differences in precipitation depths within a very few miles were defined. This characteristic led to modeling of storm-pattern distribution over the area to give a depth-area-duration model that can be used for design. Storms were indexed as related to their severity and runoff potential, so that any storm can be compared with other storms having different amount-duration combinations. The data base compiled from the network has provided the necessary information and statistical parameters on stochastic characteristics that are required for generation of synthetic data. Such data can be used to extend the rainfall and climate inputs to hydrologic models.

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Section 4.—Soil Moisture and Infiltration

INTRODUCTION

With the initial establishment of the research center at Chickasha, it was deemed necessary to instrument small unit-source watersheds to determine effects of land use, type and quality of cover, and precipitation on runoff production. Because a complete water budget was needed, soil-moisture readings were taken to determine accretions or depletions of soil water. Later, as modeling was used more and more as a research tool, we determined that a soil-moisture prediction scheme using climatic and watershed variables was desirable.

Soil moisture varied significantly from watershed to watershed, so 34 neutron access tubes were installed on a 27-acre watershed to objectively determine soil-moisture variance. The soil-moisture data indicated a great deal of variance, so a subjective study was also done.

Infiltration was also expected to vary considerably, so a project was initiated to determine the surface hydrologic variability of two grassland watersheds measured in terms of a physically based infiltration equation developed by Philip (1957). Dr. Munna Sharma, who conducted the infiltration study, also investigated the scaling of field-measured infiltration using the similar-media concept.

SOIL-MOISTURE MODELING

A dynamic model of soil moisture was developed that computes, for each day, a value of soil moisture for two zones, an upper zone of 9 inches and a lower zone of 42 inches. Gravitational flow (GF) occurs from both zones at moisture levels above "field capacity" and is calculated as daily values with the equation

$$GF = a(SM - FC),$$

where SM is the predicted soil-moisture volume on the previous day, FC is the field capacity, and a is a fitted coefficient related to permeability.

Redistribution by capillary flow (CF) between the two zones is calculated as a function of the difference in moisture content. CF is allowed to take both positive and negative values, thus indicating direction and volume of flow. The form of the equation is

$$CF = b(LSM - USM),$$

where LSM is the lower zone soil moisture adjusted to inches of water per 6 inches of soil, USM is the upper zone soil moisture in inches of water per 6 inches of soil, and b is a fitted coefficient.

The primary abstraction is due to evapotranspiration (ET), which is calculated as a function of air temperature, solar radiation, and available water in the profile. The form of the equation is

$$ET = ET_{\max} \left| \frac{TA - T_{\min}}{T_{\max} - T_{\min}} \right| \left| \frac{SR}{SR_{\max}} \right| \left| \frac{SM - WP}{FC - WP} \right|,$$

where TA is the mean daily air temperature, T_{\min} is the minimum air temperature at which the plants transpire, T_{\max} is the maximum air temperature likely to occur in the climatological record, SR is the daily solar radiation in langleys, SR_{\max} is the largest solar-radiation value likely to occur, SM is the soil moisture, WP is the soil moisture at wilt point, FC is the soil moisture at field capacity, and ET_{\max} is the maximum possible daily ET abstraction assuming maximum values for all variables. Because of the scaling from zero to 1 in each ratio, units of computation are irrelevant, since all units will give identical results. Soil moisture for the upper zone is calculated with the equation

$$SM_2 = SM_1 + (P - Q) + CF - GF - ET,$$

where P is the rainfall and Q is the runoff.

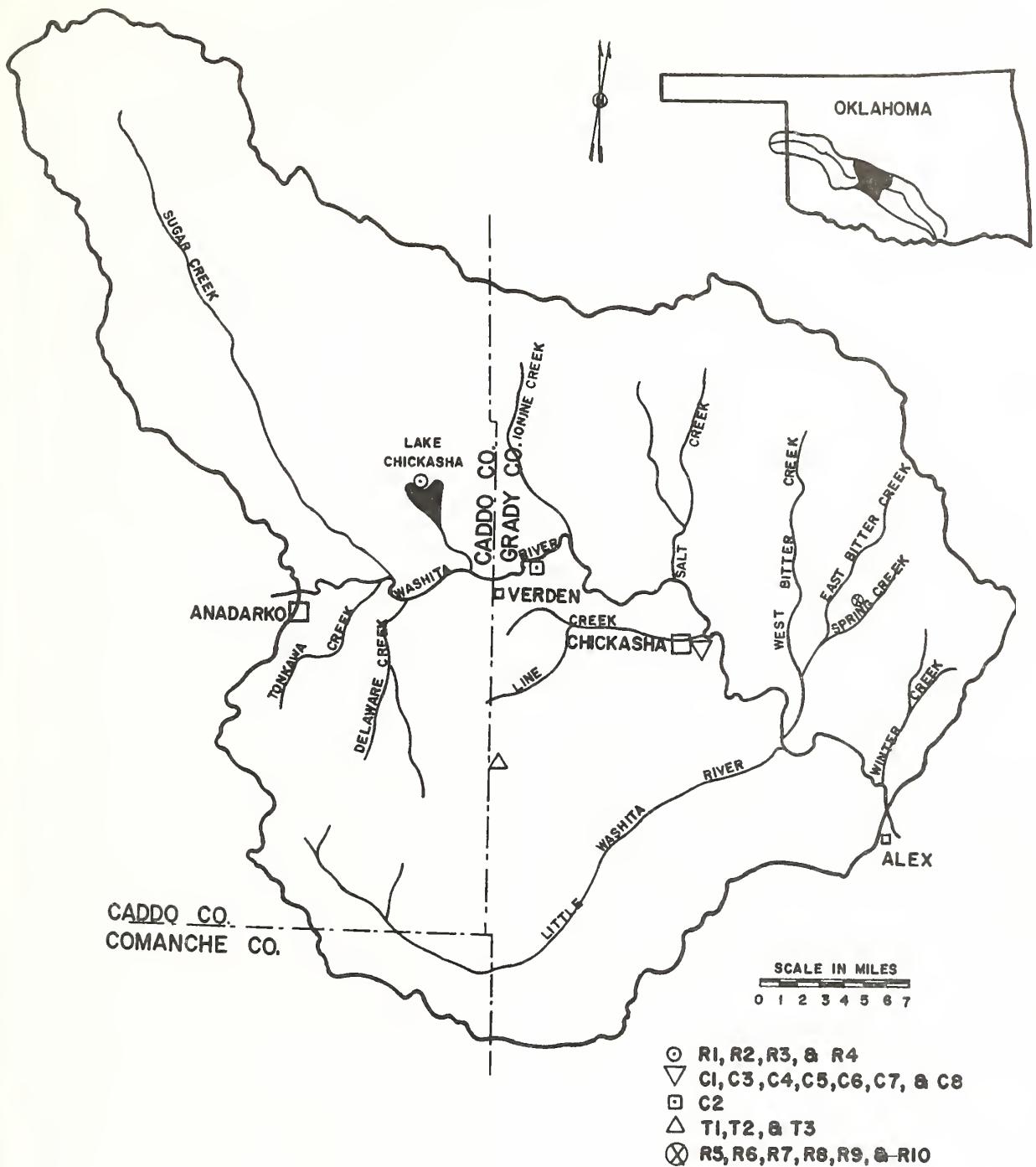


FIGURE 4-1.—Locations of unit-source watersheds within study reach.

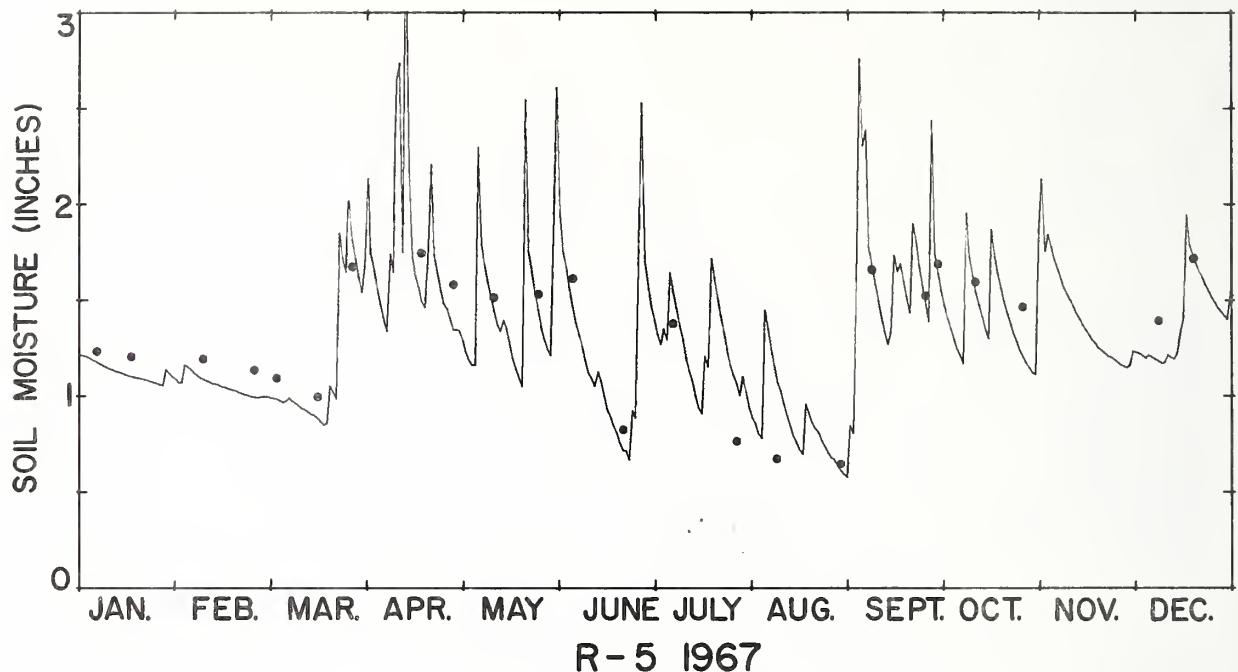


FIGURE 4-2.—Neutron-probe-measured and predicted soil moisture for watershed R-5, 1967. The dots represent neutron-probe measurements, and the continuous line is the predicted soil moisture.

The model was developed and calibrated using 1968-70 data on unit-source rangeland watershed R-5 (fig. 4-1). Validation of the model involved predicting 1967 and 1971 for R-5 and the same 5-year climatological period for rangeland watershed R-6 (fig. 4-1). The model predicted for both R-5 and R-6 with a standard error of estimate of 0.2 inch. Figures 4-2-4-4 show predicted soil moisture for R-5 for 2 years and for R-6 for 1 year.

ANALYSIS OF VARIANCE OF SOIL MOISTURE

Soil moisture within an area varies significantly because of differences in rainfall, runoff, infiltration, evapotranspiration, and soil physiographic characteristics. These variations are reflected in plant growth in pastures and croplands across the Southern Great Plains.

A study was begun in 1962 to determine the soil moisture across unit-source watersheds. These small field-size watersheds were instrumented to better understand measured variations and soil-moisture quantities available for plant

growth. The variability studies were concentrated basically on a 23.7-acre native-rangeland watershed (R-5). This area had a total of 34 soil-moisture access tubes installed to a depth of 48 inches so that soil moisture could be monitored using a neutron scattering probe. A period of intense monitoring from January 1971 to June 1974 was used as the basis for the variability studies at the Chickasha location. During the 42-month study, 84 measurements were made over the watershed. The time increments were randomly spaced and were not sampled in equal increments. Other unit-source watersheds contained two to four access tubes that could be used only for verification of findings.

The 34 tubes on watershed R-5 were distributed in such a manner that a spatial variability analysis of the soil-moisture characteristics provided some very interesting results. The analysis of variance indicated that approximately 90 percent of the variation at the 6-inch depth was due to variations within the horizontal distribution of data. This value decreased to about 70 percent when the 48-inch profile was considered. The deviations due to the other

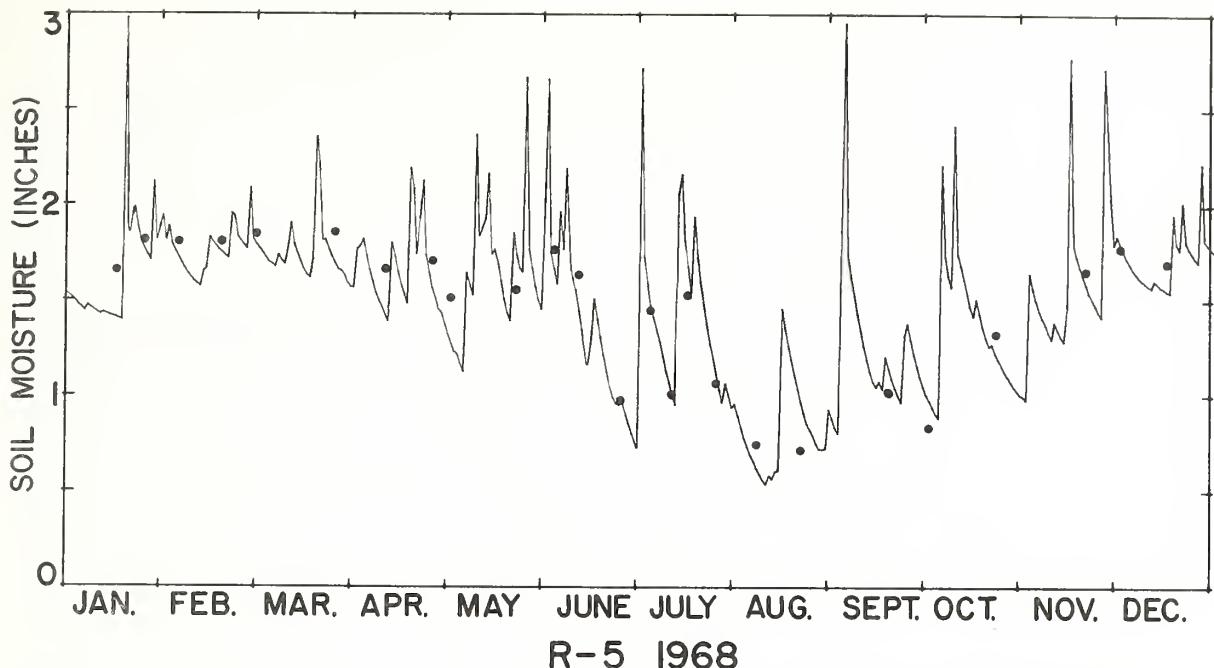


FIGURE 4-3.—Neutron-probe-measured and predicted soil moisture for watershed R-5, 1968. The dots represent neutron-probe measurements, and the continuous line is the predicted soil moisture.

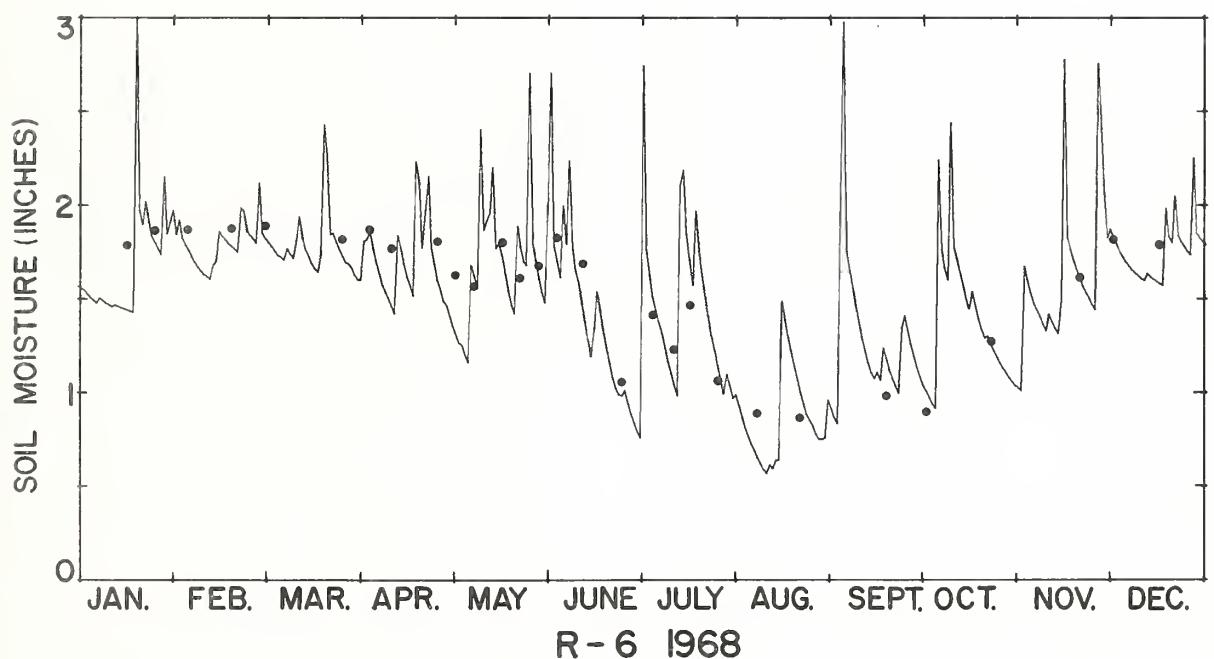


FIGURE 4-4.—Neutron-probe-measured and predicted soil moisture for watershed R-6, 1968. The dots represent neutron-probe measurements, and the continuous line is the predicted moisture.

parameters were generally less than 5 percent. The effects of seasonal variation were very significant as were the effects of surface slope. The interactions of slope and other physical aspects were also significant throughout the study. The maximum values of the coefficient of variation indicated that most of the variation (30 percent) was during the dryer seasons of the year. The wet seasons showed the lowest value of variability. All tests indicated the need for increased concern for variability of soil moisture with respect to both time and space.

Time scales should be divided into at least two periods, dormant seasons and growing seasons. Space scales can vary with depth and horizontal distances, which depend on soil types and their variations within the study area. Both time and space factors can make appreciable differences in prediction capabilities when applied to watershed hydrology models.

VARIABILITY OF INFILTRATION PARAMETERS

The goal of this project (Sharma et al. 1980) was to determine the surface hydrologic variability of two grassland watersheds, measured in terms of parameters of a physically based infiltration equation developed by Philip (1957), and to discuss the characterization of infiltration in these watersheds. Two watersheds, R-5 and R-7, were chosen for this study (fig. 4-1). More intensive studies were made on R-5 because studies on spatial and temporal variability of in situ soil moisture had been previously conducted (G. Coleman, personal communication) on this watershed. Twenty-six sites were selected on R-5 and twelve on R-7 for infiltration measurement. These sites were basically on a grid pattern with additional measurements to characterize the major soils.

Infiltration measurements were made with double-ring infiltrometers in September when the soil profile had dried out fairly uniformly. A separate, constant head device supplied water to each ring. The inner ring was 18 inches in diameter and 6 inches high, whereas the outer ring was 30 inches in diameter and 6 inches high. On the selected site, grass was cut down to 0.8 inch, and rings were driven at least 2 inches into the ground. Special care was taken to insure minimal disturbance within the inner ring.

During the time of measurement, the average water penetration was about 8 inches, which was less than half the radius of the buffer ring. Increasing the size of the buffer ring did not affect the results. Thus, during the early to intermediate time interval of zero to 60 minutes, the infiltration was essentially one dimensional.

Several mathematical expressions describe infiltration into soils. Some of these expressions are based on the physics of flow through porous media (e.g., Green and Ampt 1911, Philip 1957) and others are empirical. Philip's physically based two-parameter equation was chosen for ease of expressing time as an explicit function of cumulative infiltration and vice versa (Swartzendruber and Youngs 1979). This equation was applied to the data collected in this study. The form of the one-dimensional, vertical waterflow equation is

$$I = St^{0.5} + At, \quad (1)$$

where I is the cumulative infiltration, t is the time, and S and A are the functions of hydraulic conductivity and matrix suction head.

In this study, three methods were used to evaluate these parameters with the data on cumulative infiltration versus time.

Extrapolation method.—For very early stages of infiltration when the contribution of gravity is negligible, the second term in equation 1 becomes negligible relative to the first and thus S can be calculated as the slope of an I versus $t^{0.5}$ plot, provided the relationship is linear. For our data, over the time range $0.5 < t < 4.0$ minutes, such a relationship was linear. Values of S calculated by this method were termed S^* .

Plots of I versus t showed that, in most cases, the relationship became linear for $t > 45$ minutes, suggesting that steady state had been reached. The steady-state infiltration rate was calculated as a slope of the $I(t)$ curve at $t=60$ minutes and termed i_{60} . This was essentially the saturated hydraulic conductivity (K_s) of the surface soil. Independent measurements of K_s of some surface (zero to 6-inch) soil layers (C. Hunt, personal communication) suggested that i_{60} was slightly higher than K_s , as has been observed by others. Therefore, coefficient A of equation 1 was approximated to $i_{60}/3$ and termed A^* .

Smiles and Knight (1976) Method.—Dividing both sides of equation 1 by $t^{0.5}$ gives

$$I/t^{0.5} = S + At^{0.5} \quad (2)$$

If Philip's two-parameter equation holds, the plot of $I/t^{0.5}$ versus $t^{0.5}$ should be linear, and S and A can be easily determined as the intercept and slope, respectively, of such a line. For our data, we found that linearity between $I/t^{0.5}$ and $t^{0.5}$ held in most cases, and therefore the appropriate S and A were calculated and termed as S' and A' .

Optimization Method.—This method, developed by DeCoursey and Snyder (1969), was used to evaluate optimum values of S and A in equation 1 by an iterative reduction of the residual error associated with the estimates of the coefficient values. The coefficients so evaluated were termed S'' and A'' . These are statistical techniques, thus physical significance could not be assigned to the parameter sets evaluated by this method.

Under most field conditions, S^* and K_s (and therefore A^*) can be measured easily and reliably (Talsma 1969), whereas complete infiltration data are required for evaluation of S' and A' or S'' and A'' . Thus, use of S^* and A^* would be preferred. Both sorptivity (S^*) and parameter A (A^*) so evaluated have distinct physical meanings. Sorptivity takes into account the hydraulic properties of soil ($\psi(\theta)$ and $K(\theta)$) and the initial and final water content, whereas parameter A is specifically related to steady-state infiltration or saturated hydraulic conductivity.

The $I(t)$ relationship for each site we measured can be adequately expressed in terms of sorptivity and coefficient A of equation 1. Spatial variation in these parameters over watershed R-5 suggested no definite pattern in the distribution of these parameters. There was a band of higher S^* and A^* (higher intake area) on the outer edges of the upper part of this watershed. Otherwise, there was a fairly random distribution, irrespective of soil type or position, over the remainder of the watershed.

Variations in sorptivity over watersheds R-5 and R-7 were within one order of magnitude, and variations in A were within two orders of magnitude. Similar variations in these or similar parameters have been reported (Talsma 1969, Nielsen et al. 1973, Rogowski 1972). The variability of parameters was of similar magnitude for both watersheds. The coefficient of variation of logarithm A was considerably reduced, but similar transformation of S resulted in an increased coefficient of variation. This occurred

because values of S are close to 1, so logarithms take negative as well as positive values.

So that hydrologic parameters can be averaged or lumped meaningfully, it is appropriate to examine the properties of these parameters as regards their relationships with each other and also their distribution functions. In general, there is a tendency for S^* to increase with increasing A^* . Talsma (1969) reported poor relationship between sorptivity and saturated hydraulic conductivity.

Considering watershed R-5 as one soil unit, the frequency distributions of S^* , A^* , and I , measured at various time intervals, were examined. The frequency distributions of both infiltration parameters and I at $t=30$ minutes were better approximated by a log-normal fit than by a normal fit. Similar results were obtained for both infiltration rates and cumulative infiltrations examined at other times.

Since A^* is closely related to saturated hydraulic conductivity, its distribution function is in accord with other observations (e.g., Rogowski 1972, Nielsen et al. 1973). Although sorptivity is a much less varying parameter, its distribution is also closer to log normal. Log-normal distribution for S has been suggested (Brutsaert 1976), but it has not been demonstrated with experimental data. However, it appears that assuming normal distribution for S may not introduce as much error as a similar assumption of hydraulic conductivity for A .

Composite $I(t)$ functions based on 26 infiltration tests for the whole watershed (R-5) and separately for 3 soils were calculated, the calculations being based on arithmetic as well as geometric means of S^* and A^* . In this case, composite curves, based on arithmetic and geometric means of the parameters, were not significantly different.

The infiltration behaviors of Renfrow and Grant silt loams were very similar, and their infiltration parameters were higher than those of Kingfisher silt loam. However, Kingfisher occupies only a small portion of the watershed where only three measurements were made, one of which revealed an exceptionally low infiltration rate that represented a negligible fraction of this soil.

For hydrologic consideration, the whole watershed can be assumed to have one soil type, since the variability differences among these soils are marginal. This does not conflict with the Soil

Conservation Service classification that identifies these soils because it is not primarily based on surface hydrologic considerations. However, these conclusions should be treated with caution, since they are based on the assumption that measured infiltration behavior within and between soils does not interact. Perhaps the significance of identifying several hydrologically different areas can be better assessed by looking at their effect on the hydrologic response of the watershed.

SCALING OF FIELD-MEASURED INFILTRATION

Infiltration curves measured at 26 sites on R-5 were all adequately characterized by Philip's two-parameter equation, $I=St^{0.5}+At$, where I is the cumulative infiltration, t is the time, and S and A are the two parameters. These infiltration data, comprising 618 observations, were scaled according to the concept of similar media, and one value of similar media and one value of scaling factor were assigned to the infiltration data of each site (Sharma et al. 1980).

The theory of similar media demands that soils at different locations in the watershed must have identical porosity and the same relative pore-size distribution and that these characteristics do not change with time or degree of saturation (Miller and Miller 1956). However, in practice soils do vary with respect to porosity and exhibit some shrinking or swelling with varying degrees of saturation. Therefore, it should be emphasized that field soils will never fully satisfy the conditions required by the similar-media theory.

Our studies demonstrate that, with some approximations, the similar-media concept can be used fairly successfully to scale field-measured infiltration data. This allows the expression of the spatial hydrologic heterogeneity in terms of a single physically based parameter, the normalized scaling factor. Further work may be required to determine whether the same scaling factors could be applied in scaling other soil-water properties, such as water retention ($\psi(\theta)$) and unsaturated hydraulic conductivity ($K(\theta)$). If this were true, calculation of scaling factors from simple infiltration tests would offer a rather convenient method for generating basic soil hydraulic

properties ($\psi(\theta)$ and $K(\theta)$), the determination of which is otherwise both time-consuming and tedious.

Theoretically, either of the infiltration parameters (S or A) could be used in calculating scaling factors, and these should be identical if all the demands of similar media are satisfied. However, in this study the scaling factors α_S based on S and α_A based on A , although correlated to some extent, were not identical. Better scaling was achieved with α_A than with α_S . This difference may be attributable to changes in porosity and pore-size distribution with saturation as infiltration proceeded and also to inherent variation in initial soil water content, which affected S and not A . Apparently, scaling of infiltration based on α_A would be preferred over that based on α_S . However, scaling was considerably improved when some average of α_A and α_S was used. This indicates that both early- and late-stage infiltration parameters need to be considered and that scaling by only one of these parameters may be invalid. The fact that geometric (α_{SA}^G) and harmonic (α_{SA}^H) means did better scaling than the arithmetic mean (α_{SA}) in this study suggests that equal weighting is not required for early- and late-stage parameters. More research is required to fully answer questions raised by the above discussion.

In a recent analysis, Warrick et al. (1977) reported that the scaling factors calculated to scale $\psi(\theta)$ data of field soils were not the same as those calculated to scale $K(\theta)$ data of the same soils. This discrepancy could not be explained. They found that scaling factors calculated from $\psi(\theta)$ were more effective in scaling the unsaturated hydraulic conductivity data than were the scaling factors from $K(\theta)$ in scaling soil water retention data. The considerably larger variability in the scaling factors from $K(\theta)$ compared to those from $\psi(\theta)$ was attributed to the fact that K was more sensitive to variation in θ than was ψ and also that the experimental techniques for measuring K in the field were not as well developed as those for ψ . In our case, scaling factors calculated from S exhibited much larger variability than those calculated from A . This may primarily be because S was much more sensitive to variable initial soil water conditions than was A , although the magnitude of spatial variability in A was usually much larger than in S .

SUMMARY

Soil moisture can be modeled to improve prediction of storm antecedent conditions, although more development would be required to make the model presented herein more universally applicable. A need for increased concern over soil moisture variability has become apparent. Both time and space factors can make appreciable differences in prediction capability when applied to watershed hydrology models.

Philip's two parameters did fit measured infiltration on watersheds R-5 and R-7. Variations in sorptivity were within one order of magnitude, and variations in A , which is related to saturated hydraulic conductivity, were within two orders of magnitude.

We found that the similar-media concept can be used fairly successfully to scale field-measured infiltration data. Scaling in this study based on A of Philip's equation gave better results than scaling based on S . However, scaling was improved when some average of α_s and α_A was used. The scaling factors were log-normally distributed.

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Section 5.—Remote Sensing of Hydrologic Parameters

INTRODUCTION

Reliable projections of the quantity and rate of runoff from the surface of the land into rivers and streams are difficult to obtain for ungaged watersheds. However, this information is needed in the design of any structure located in the vicinity of a water course; for example, the storage capacity of municipal water supplies and floodwater-retarding structures. When projections of runoff are questionable, the storage capacity of such structures is quite often overdesigned. Overdesign not only increases construction costs but may also lead to significant reduction in the flushing action needed to maintain good water quality in structures where inflow is initially saline and evaporation rates are high.

Since the use of mathematical models is the best way to analyze data when trying to describe the hydrologic processes, much effort has been put forth to develop and evaluate models for separate segments of the hydrologic cycles. Remote sensing has been used on the Chickasha watersheds to investigate the spatial variability and monitoring of soil moisture and surface water stored within the watershed. Special emphasis has been placed on prediction of soil moisture. Some research has also been done on pond water quality, geology, and water seepage.

SOIL-MOISTURE ESTIMATIONS FROM AIRCRAFT DATA

During the initial phase of the soil-moisture studies, the relationships between digital data from aircraft and satellite overpasses were not established; therefore, the first studies at Chickasha were made to determine these relationships. Not only were new sampling procedures needed

but also processes to utilize computer facilities for separating and assessing data in a usable manner. This led to several improvements in data processing procedures for remotely sensed data (Blanchard 1972).

Procedures.—The first remotely sensed data gathered over the Chickasha watersheds was by National Aeronautics and Space Administration (NASA) aircraft in September 1969 (Blanchard 1972). An RB57 aircraft flew the entire watershed at an altitude of 60,000 feet and collected color and color infrared photographs. Also, an NP3A aircraft passed over selected data lines at 3,000 feet and collected microwave line scans in several frequencies, as well as infrared data and color photographs.

Soil samples were collected in fields below the lines of flight while the aircraft were collecting data. These samples were taken from large bare fields and were sealed in plastic bags and marked appropriately. As soon as the samples were received in the laboratory, they were processed to find soil moisture on a dry-weight basis.

Analyses.—The aircraft data were analyzed to compare several of the different types of data with the surface soil-moisture values taken from each separate field. For example, the X, L, and KA bands, which had 2.8-, 20-, and 1-centimeter wavelengths, respectively, were plotted versus soil-moisture values read over an entire field. By combining bands, finding differences between bands, and establishing other such mathematical relationships, analyses were made not only with respect to soil moisture but also for vegetative cover.

Results.—Antenna temperatures of the microwave radiometers, which are the actual measurement of energy reflectance, proved to be well related to soil moisture at the zero to 6-inch level on bare ground. The analyses indicate that remote sensing, using X-band microwave data, is

a good indicator of soil porosity for hydrologic modeling.

RUNOFF PREDICTIONS FROM SATELLITE MULTISPECTRAL DATA

Underdesign of the floodwater-retarding structures can cause loss of life and property if the dams break, and these structures can cost extra money to build when they are greatly overdesigned. The use of remotely sensed data might be used to take some of the subjectivity from the design parameters and better insure an adequately designed dam at the lowest possible cost.

During the period of July 1, 1972 to July 1, 1974, an investigation was made at the Chickasha watersheds to identify differences in watershed runoff capability using spaceborne Earth Resources Technology Satellite (ERTS) sensors (Blanchard 1974). These differences reflect the storage of water in or near the soil surface over a large nonhomogeneous area.

The model chosen for study was based on Soil Conservation Service (SCS) runoff curve numbers. This model predicts runoff from a watershed so that flood-retarding structures can be designed. It uses human judgment to determine some parameters needed for the storage values in the model. These include hydrologic condition of the cover and hydrologic classification of the soils.

Procedures.—Hydrologic and ground data used for this study were collected by the Agricultural Research Service (ARS) from 1961 through 1972. The data represent contributions from 20 watersheds within the study area. Data from 10 of the watersheds (group I) were used to calibrate the model parameters. Accuracy of the model was then verified by application on the other 10 watersheds (group II). The data included Theissen weighted rainfall, runoff, antecedent rainfall index (30-day delayed), antecedent rainfall index (5-day sum), and maximum hourly intensity. These data were taken from 256 storm events during the period of record. Other factors used included drainage areas controlled by farm ponds (taken from topographic maps), extent of range-land bare ground, and mean daily temperatures.

These data were used to calculate actual curve numbers for each storm event using the SCS runoff equation

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}, \quad (1)$$

where $S = 1,000/CN - 10$,
 $Q = \text{storm runoff (centimeters divided by 2.54)}$,
 $P = \text{Theissen weighted storm rainfall (centimeters divided by 2.54)}$,
 $S = \text{potential maximum retention of rainfall including the initial abstraction (centimeters divided by 2.54)}$,
and $CN = \text{runoff curve numbers, an index of the effect of soil, cover, and antecedent moisture on runoff}$.

Most of the runoff events studied were in the class I category of antecedent precipitation index used by SCS. Therefore, only storms occurring at times of class I antecedent precipitation were used to derive mean curve numbers for watersheds in this study.

Curve numbers had previously been determined by SCS for 12 of the 20 watersheds under study. Therefore, these data were obtained from SCS along with soils maps and photomosaics so that curve numbers for the remaining eight watersheds could be computed by the conventional SCS methods. Land use was determined using photographs of the watersheds, which allowed weighted mean curve numbers to be calculated for this study.

A second equation was developed to predict runoff using only precipitation and 30-day antecedent precipitation. Using all 256 storm runoff events, the resulting equation using linear regression techniques was

$$Q = CP^{2.15} API^{0.278}, \quad (2)$$

where $Q = \text{watershed storm runoff (centimeters divided by 2.54)}$,
 $C = \text{a dimensionless coefficient representing differences in watershed conditions}$,
 $P = \text{weighted mean storm rainfall (centimeters divided by 2.54)}$,
and $API = 30\text{-day delayed antecedent rainfall index derived using inverse temperature curves to adjust for seasonal variations (centimeters divided by 2.54)}$.

The above equation proved to be about equal to

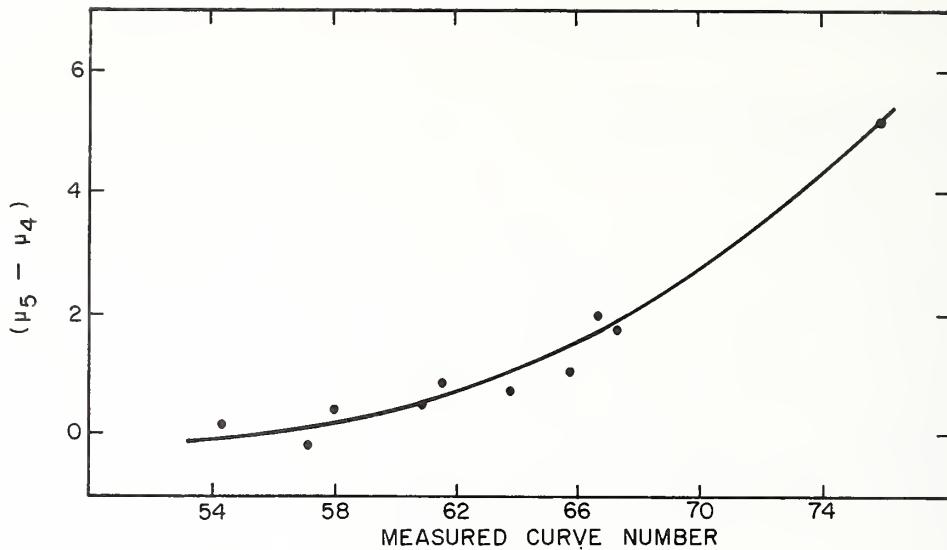


FIGURE 5-1.—Relation of MSS data to measured watershed-runoff curve numbers.

the SCS curve-number model for predicting runoff in the Southern Great Plains.

Aircraft multispectral digital data for the watersheds were obtained to differentiate and enhance physiographic and land-use practices within the study area. Computer programs were used to calculate statistical values for use in the analyses.

Analyses.—Multiple discriminant analysis was used to study group similarities and differences within the watershed. When each of the 10 research watersheds in group I was considered, the multiple discriminant analyses showed very significant group discrimination. However the discrimination did not appear to be related to runoff coefficients.

Plots made of the mean value for each band versus the observed runoff coefficients showed that the mean of remotely sensed multispectral scanner (MSS) band 5(μ_5) minus the mean of MSS band 4(μ_4) was well correlated to the measured SCS runoff curve numbers (fig. 5-1) for the research watersheds in group I.

Curve numbers were then predicted for the group II watersheds by using the relationships developed from data for group I. The predicted values and the conventional SCS curve numbers were plotted versus the measured curve numbers. The average deviation of the predicted values from the measured curve numbers was 4.59 units (absolute) when using two bands of MSS data and 3.70 units (absolute) when using four bands of

data. A comparison of the average deviation of the predicted values with an average deviation of 10.72 units between the conventional and measured values shows the superiority of using remotely sensed data over the conventional procedure.

As a further check of the prediction scheme, the MSS data for Sugar Creek watershed (test station 121) were analyzed. Using a mean difference between bands 4 and 5 that was calculated for each watershed, a predicted runoff curve number for each of the subwatersheds was obtained. The conventional SCS curve numbers and predicted values were plotted versus the measured curve numbers to illustrate the improvement possibilities using the ERTS-MSS data (fig. 5-2). The average absolute deviation of predicted values from the measured runoff curve numbers was 10.18 units. Average deviation of the conventional curve numbers for the subwatersheds was 24.08 units. Figure 5-2 shows that only 3 of the 22 subwatersheds had predicted values slightly under their measured values.

Results.—The multiple discriminant analysis routine used in this study was an excellent research tool, using the high and low runoff-producing watersheds to indicate feasible linear combinations of the MSS data. However, the system did not necessarily indicate the best linear combinations for prediction of the dependent variable when several watersheds were considered.

Equation 2 was developed as an empirical model to predict storm runoff better than the SCS runoff equation. However, the available data from the 20 watersheds did not produce an equation that adequately represented the runoff process; thus, the SCS model was still the better predictor.

The lack of accurate watershed ground truth data was the limiting factor in development of watershed-runoff estimates. The range of runoff capacities on small watersheds was not sufficiently covered in the lowest and highest curve-number areas. However, the study indicated that the technique produced repeatable results in situations where dry conditions existed, especially where all bands of data were used. Underprediction occurred less frequently with the four-band system. Substantial proof of the validity of the technique was shown in using the Sugar Creek subwatershed, where ERTS data reduced the overestimation of curve numbers by a factor of 2.36.

This study has shown that, when dry surface conditions exist on watersheds in this area, linear combinations of MSS digital data can be related to the watershed runoff coefficient used in the SCS storm-runoff equation. Also, predictions based on the relationship between ERTS-MSS data and measured watersheds can improve SCS runoff curve numbers by more than a factor of 2 over curve numbers calculated by the subjective conventional methods. The improvement in estimating curve numbers can significantly refine the estimates of runoff that are necessary for the design of flood-control structures.

RUNOFF PREDICTIONS FROM PASSIVE MICROWAVE DATA

Additional data were collected during April and June 1973. An airborne passive microwave imaging scanner (PMIS) was flown over the watershed in an aircraft operated by NASA.

The PMIS is an X-band (10.69-gigahertz-frequency or 2.8-centimeter-wavelength) scanning radiometer. Passive microwave systems measure the emission of radiant energy from a surface created by atomic and molecular oscillations in the observed material. A previous experiment (Conway and Yarbrough 1966) showed that microwaves can penetrate into soils a few cen-

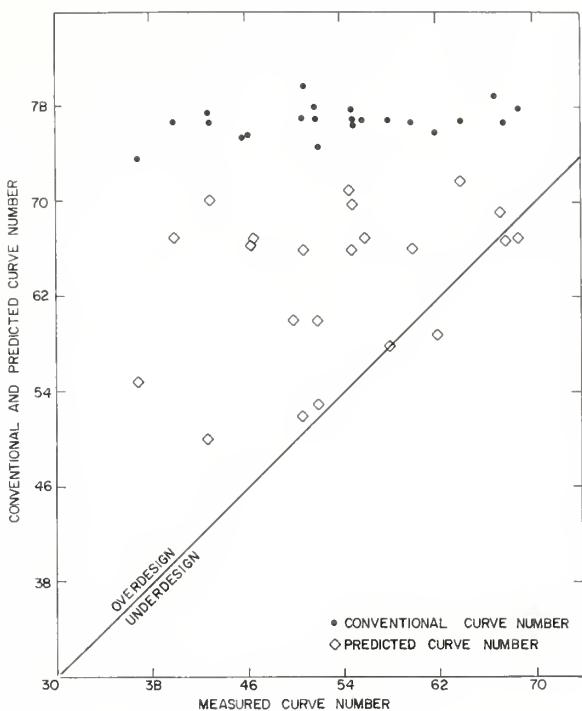


FIGURE 5-2.—Conventional SCS 'class I' runoff curve numbers and predicted curve numbers using two bands of ERTS-MSS data versus measured curve numbers.

timeters. However, it may not be possible to detect subsurface moisture if it is covered by a dry layer.

The watershed variable selected for comparison with passive microwave measurements was again the coefficient (CN) used by SCS. The plan in general was to collect passive microwave vertical and horizontal polarization data, surface temperatures, and simultaneous aerial photographs to verify location of the aircraft over eight watersheds within the study reach of the Washita River basin (Blanchard et al. 1975). Two consecutive NASA flights were requested, one representing wet conditions and the other dry conditions. Flight requests stipulated that time between flights should not allow major changes in vegetative growth and that weather conditions for both flights should be clear.

Procedures.—Watershed data for the study were taken from Agricultural Research Service (ARS) records for the East Bitter Creek and Sugar Creek watersheds. Five of the subwatersheds (5141-5144 and 5146) are located on East Bitter Creek (fig. 5-3), and the remaining three

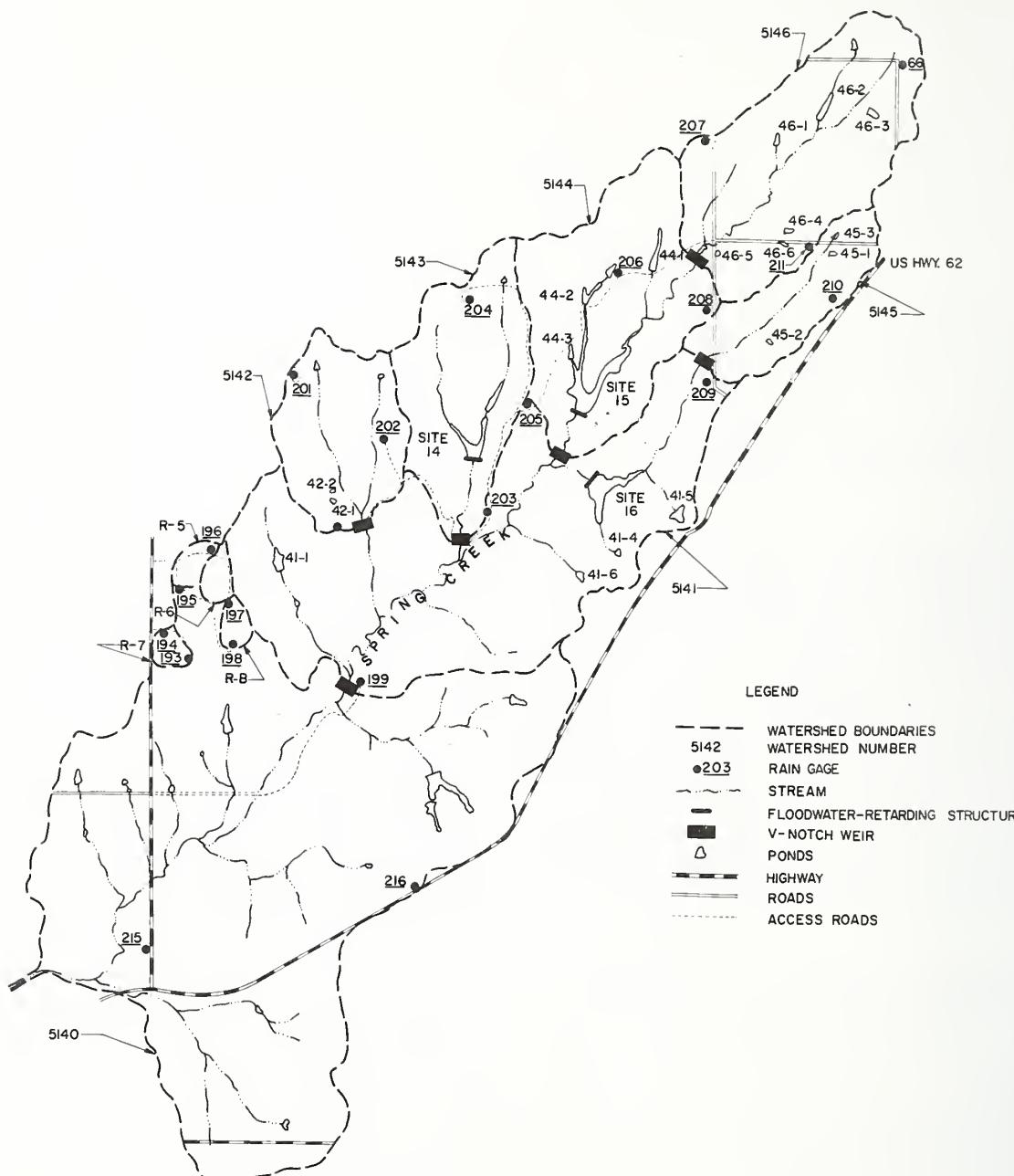


FIGURE 5-3.—Detailed map showing subwatersheds on East Bitter Creek watershed. Spring Creek is included in the East Bitter Creek watershed.

Table 5-1.—Characteristics of subwatersheds on East Bitter Creek and Sugar Creek

Characteristic	Subwatershed number ¹							
	5141	5142	5143	5144	5146	13	15	25
Drainage area km ²	16.45	1.46	1.97	5.92	3.08	5.15	9.92	8.11
Area above farm ponds pct	22.8	7.28	33.4	38.0	29.2	5.49	4.31	8.13
Number of rain gages	17	8	4	9	6	3	3	2
SCS runoff coefficient (CN)	61.5	59.4	56.3	62.8	63.8	46.0	37.0	51.0

¹Watersheds 5141-5144 and 5146 are on East Bitter Creek. Watersheds 13, 15, and 25 are on Sugar Creek.

(13, 15, and 25) are located on Sugar Creek (fig. 2-1).

Using these data, the SCS runoff coefficient (CN) was calculated for selected storms for each watershed and then averaged to arrive at a single coefficient representing the average response for each watershed. These average coefficients are listed for each watershed in table 5-1.

The two sets of data taken with NASA's PMIS system were analyzed to determine average vertically polarized and horizontally polarized antenna temperatures across each watershed for both flights. Because of the large number of data points within each watershed, the temperatures measured by the PMIS system represent a very precise measurement when compared with those of 20 storm events from each watershed that were used for ground truth values. This results in a rather crude comparison. However, the results show a very definite improvement in coefficient estimation techniques resulting from remote sensing.

Results.—Three of the structures on the subwatersheds were designed and built by SCS using curve numbers 76, 74, and 77; however, measured storm values using the remote-sensing techniques indicate that coefficients or curve numbers 46, 37, and 51, respectively, should have been used. In this instance, coefficients 26 to 37 units too large were used, which resulted in an overdesigned and expensive structure.

Overdesign would be significantly reduced in the future if overestimation of the runoff coefficient could be reduced to 10 units or less without permitting the hazards of underdesign. Since this experiment involved only eight watersheds, the results can only be viewed as a pilot effort, and further testing of the promising relationships should be undertaken.

Conclusions.—A sensitive relationship between

average PMIS microwave temperatures over a watershed surface and the SCS watershed storm-runoff coefficient may be developed using the average horizontally polarized temperatures from a single flight made during the dormant or early growing season of the year. This relationship could be used to develop predictions of coefficients.

The differences between horizontally polarized PMIS temperatures from two flights over the same watershed, when vegetation and antecedent moisture conditions were different, were related to the SCS runoff curve number and could be used to develop a prediction scheme for such coefficients.

Further testing of this concept of watershed calibration is warranted using the PMIS system or microwave imagers capable of sensing longer wavelengths. The testing could extend over a 1-year period to determine the most appropriate time of year for taking the microwave data.

WATER-QUALITY STUDIES

Since remote-sensing data collection is not limited to land areas, data collected having information on ponds and surface-water areas were analyzed to try to determine differences in concentrations of suspended sediments in reservoirs. Sediments are recognized as a major pollutant of water; therefore, it is desirable to quantify the suspended clay particles in lakes and ponds.

The objective of this experiment, using the data from the 1969 flights, was to select the wavelengths most suitable for measuring suspended sediment loads and to determine if common dissolved pollutants in local lakes and ponds could be detected by photographs and infrared scanner imagery (Blanchard 1975a, 1975b).

Procedures.—The data collected in this study were compared with samples taken from 17 ponds located along the flight lines. The samples were collected about the time of the overpasses to eliminate water temperature changes. Temperature readings were taken on the water surfaces at the time of sampling. The samples were analyzed for total salts, specific salt constituents, and sediment concentrations.

Results.—Analyses of the infrared response from ponds where water-quality samples were available did not reveal any means of identifying common dissolved pollutants indigenous to this area. The response of the film was totally dominated by the suspended sediments in the water. The percentage of incident light reflected in the visible light part of the spectrum from water containing suspended sediment varied with differences in concentrations at relatively low sediment loads. These results indicate that reliable estimates of sediment (clay and fine silts) in ponds and lakes can possibly be monitored by aerial photography.

PREDICTING SEDIMENT CONCENTRATIONS IN RESERVOIRS

During the remote-sensing flights by NASA in 1971, samples were again collected to try to detect pollutants in farm ponds and small reservoirs. These were compared with samples collected from the Texas Blacklands near Temple, Tex., and from ARS's research farm near Weslaco, Tex. (Blanchard and Leamer 1973).

Procedures.—Samples collected from these sites were compared by using a truck-mounted radiometer that scanned the samples, which consisted of several different concentrations of sediment in clear tap water. The samples were subjected to spectral scan at different sun angles and different wavelengths to try to optimize the detection of pollutants.

The data taken by aircraft on infrared film were also analyzed to again try to detect different pollutants. The film was analyzed by using optical density techniques. Different filters were used on the infrared cameras to determine the extent to which the filters would improve the sensitivity of the film to the pollutants.

Results and discussion.—Photographic measurement of suspended sediments imposes

problems that may be difficult to resolve. Corrections for atmospheric effects on the photography have been made by the Cornell Aeronautical Laboratories (Piech and Walker 1971) with some success. Lens, filter, film stability, and film development techniques, along with aircraft flight parameters and sun angle, can alter film optical density.

In this study, these parameters were held relatively constant or did not exist in photographs made over the controlled samples; however, they would become important in measuring sediment over large areas.

The use of narrow band multispectral scanners to measure suspended sediment in water offers more promise than the use of photographic techniques. Film and development problems could be eliminated; however, aircraft flight parameters, atmospheric attenuation, and sun angle would still affect the data. The selection of narrow wavelength bands and analog to digital conversion of data are advantages of the airborne scanners. Use of a band centered near 570 nanometers and one or more bands near 690 nanometers would provide a data base for systems to measure low concentrations of sediment while simultaneously detecting the presence of algae.

The detection of other water-quality parameters may be very difficult to accomplish in waters carrying even minor loads of suspended sediments. The large change in reflectance caused by 9-part-per-million concentrations of suspended sediments from the Texas Blacklands compared with reflectance from clear water might have precluded detection of another contaminant. If another contaminant could have been identified by a characteristic anomaly in its spectral reflectance, such as was found for algae, its presence may have been determined. It is also important that any technique developed for measurement of suspended sediments be controlled by sampling, or a system must be developed to reduce sediment color from spectral measurements.

Conclusions.—Measurement of suspended sediments in water is feasible for concentrations up to approximately 75 parts per million, depending on the color and source of the sediments. The use of instruments having a band centered near 570 nanometers and one or more bands near 690 nanometers would provide adequate data to detect sediment and algae. Ratioing responses between two or more bands appears to be essen-

tial to the detection of both algae and suspended sediments. Remote sensing of heavy concentrations of suspended sediments with visible or near-infrared light is not feasible and may produce misleading results.

SUMMARY

The results of remote sensing using aircraft and satellite techniques are a valuable tool in watershed and hydrology research. Remote sensing is a sensitive indicator of rainfall storage determined by the porosity of the soil in a watershed, which is useful in hydrologic modeling.

When the results of remote sensing were applied to studies using the SCS curve-number model, they aided in predicting curve numbers such that benefits of several thousands of dollars in savings could possibly be achieved over a watershed treatment area. The curve numbers over the entire watershed were reduced by an average of 2.36 units, while an individual treatment area had reductions of 26 to 37 units.

Over-design could be significantly reduced if the overestimation of the runoff coefficient (*CN*) could be reduced to 10 units or less without the hazards of underdesign. Results of this study are applicable only in the area studied; additional data should be obtained in other areas.

The differences between horizontally polarized PMIS temperatures from two flights over the same watershed, when vegetation and antecedent moisture conditions were different, were related to the SCS runoff curve number and could be used to develop a prediction scheme for such coefficients.

Analyses of the infrared response from ponds where water-quality samples were available did not reveal any means of identifying dissolved pollutants indigenous to this area. The response

of the film was totally dominated by the suspended sediments in the water.

Measurement of suspended sediments in water is feasible for concentrations up to approximately 75 parts per million, depending on the color and source of the sediments. Remote sensing of heavy concentrations of suspended sediments with visible or near-infrared light is not feasible and may produce misleading results.

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Section 6.—Hydrology of Unit-Source Areas

INTRODUCTION

The tributary watersheds of the Washita River are heterogeneous in nature. They consist of an array of varying hydrologic parameters that influence surface runoff, including soil, slope, land use and size, and shape of drainage networks. These tributaries may be considered as consisting of numerous subwatersheds or so called unit-source watersheds.

A unit-source watershed is an intermediate area between small plots, in which certain generative processes can be isolated, and large tributary watersheds where storm runoff and water yield are controlled by the hydraulics of many complex parameters. A unit-source watershed may be defined as a drainage area that has relatively homogeneous soil, vegetation, slope, exposure, and land use. It is subject to essentially uniform precipitation from any particular storm event and is an area in which geologic influences on surface flow are really representative. Such an area could also be defined as physically homogeneous, with a single type of soil having a single land use.

To better understand some of the major hydrologic variables encountered in the larger tributaries, several unit-source watersheds were selected and instrumented to provide input parameters for the development and testing of hydrologic models. The variations in soils, land use, and other hydrologic parameters within the 1,130-square-mile Washita study reach were so numerous that it was impractical, if not impossible, to establish small watersheds to represent all conditions. Therefore, the following five major land-use sites were selected as the most prevalent from a hydrologic point-of-view:

1. Upland grassed areas (formerly cultivated) on fine sandy loam soils.
2. Upland grassed areas (never plowed) on silt loam soils.
3. Upland grassed areas (formerly cultivated), eroded, on silt loam soils.

4. Upland brush or blackjack oak areas on fine sandy loam soils.

5. Cultivated bottom-land areas on silt loam to silty clay loam soils.

A total of 21 unit-source watersheds (fig. 4-1) were studied within these 5 major land-use sites; they are discussed below.

UPLAND GRASSED AREAS ON FINE SANDY LOAM SOILS

Four small grassland watersheds (R-1 through R-4), ranging in size from about 18 to 26 acres and consisting of fine sandy loam soils with slopes of about 3 to 8 percent, were established July 1, 1962 and continued in operation until July 1, 1974. These watersheds are located in Caddo County, about 8 miles northwest of Verden, Okla., near the confluence of Spring Creek and Stinking Creek. The soils are Noble, Dill, and Darnell fine sandy loams and are deep, well drained, and moderately permeable. These four watersheds are in the Central Great Plains on the silt-sandy loam side of the Reddish Prairie land resource area.

The watersheds were within the same pasture and were subjected to continuous uncontrolled overgrazing. A small portion of each was cropped during the period 1907-40. The average vegetative cover was generally considered to be good hydrologically, averaging 2 to 3 tons per acre total dry matter throughout the period of record. The range-condition classification was poor throughout the 12-year study. The cover consisted mostly of annual weeds and grasses and low-order perennial grasses. In addition, there was a considerable amount of pocket gopher activity, which decreased the runoff potential. There were no gullies or eroded areas.

Runoff quantities for individual events were computed from storage in small farm ponds at

Table 6-1.—Average monthly precipitation (*P*) and runoff (*Q*), in inches, for upland grassed areas on fine sandy loam soils in 12-year study¹

Month	Watershed							
	R-1 (17.8 acres)		R-2 (24.1 acres)		R-3 (25.8 acres)		R-4 (18.1 acres)	
	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>
January	0.81	0.000	0.76	0.001	0.74	0.000	0.78	0.000
February	1.06	.001	.99	.002	.98	.001	1.01	.001
March	2.05	.003	1.87	.006	1.86	.002	1.88	.001
April	2.92	.012	2.77	.037	2.74	.015	2.91	.046
May	3.68	.014	3.47	.028	3.40	.010	3.68	.014
June	2.97	.028	2.84	.036	2.80	.011	3.02	.014
July	1.71	.001	1.63	.001	1.59	0.000	1.65	0.000
August	2.90	.004	2.74	.023	2.69	.010	2.80	.016
September	4.18	.006	3.96	.027	3.90	.012	4.11	.014
October	2.50	.002	2.35	.008	2.34	.003	2.46	.003
November	1.63	.002	1.58	.008	1.56	.004	1.59	.003
December .....	.90	0.000	.83	.003	.83	0.000	.87	0.000
Avg. ann. amt....	27.31	.073	25.79	.180	25.43	.068	26.76	.112
Max. rain ²	8.65	.004	8.22	.151	8.18	.019	8.07	.091
Max. runoff ³	2.93	.257	6.29	.217	6.29	.096	6.35	.305

¹Basic data are from USDA Miscellaneous Publications 1216, 1226, 1262, 1330, 1370, and 1380 (1965 through 1970).

²High precipitation month: R-1 and R-3, August 1966; R-2, September 1966; R-4, September 1967.

³High runoff month: R-1 and R-3, June 1970; R-2, August 1965; R-4, April 1967.

the lower portion of each watershed. Table 6-1 is a tabulation of the 12-year monthly average rainfall and runoff data. The runoff amounts were very low throughout the period. The maximum monthly rainfall of 8.65 inches, which occurred in August 1966, produced only 0.004 inch of runoff. The maximum monthly runoff of 0.305 inch, which occurred in April 1967, resulted from a monthly rainfall of 6.35 inches.

Additional available data from these sites include daily, monthly, and yearly precipitation; storms; monthly and annual runoff; vegetative cover; periodic soil moisture; and topographic and soil survey maps (Moffatt 1973).

UPLAND GRASSED AREAS ON SILT LOAM SOILS

Four small grassland watersheds (R-5 through R-8), ranging in size from about 19 to 28 acres and consisting mostly of silt loam soils with average slopes of about 3 percent, were estab-

lished July 1, 1966 and continued in operation until July 1, 1978. These watersheds are located in Grady County, about 11 miles northeast of Chickasha, Okla., in the East Bitter Creek watershed and are representative of the Reddish Prairie land resource area.

Watersheds R-5 and R-6 were native grassland areas within a pasture that had never been plowed. These two areas were subjected to a grazing intensity that was slightly greater than desired. The total vegetative cover ranged from about 1.5 to 4 tons per acre and averaged about 2.5 tons per acre for the period of record.

The soils in R-5 and R-6 are a complex of Grant silt loam, Renfrow silt loam, and Kingfisher silt loam (eroded) and are moderately permeable.

Watersheds R-7 and R-8 were cultivated from about 1907 until the early 1940's, when erosion had become severe. They were in pasture after that, and a fair to good stand of native grass was established. However, because of low fertility and continued uncontrolled overgrazing, very little

Table 6-2.—Average monthly precipitation (*P*) and runoff (*Q*), in inches, for upland grassed areas on silt loam soils¹

Month	Watershed ²																	
	R-5 (23.7 acres)			R-6 (27.2 acres)			R-7 (19.2 acres)			R-8 (27.6 acres)			R-9 (9.3 acres)			R-10 (1.5 acres)		
	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>		
January	0.90	0.032	0.91	0.016	0.89	0.121	0.92	0.061	0.88	0.159	1.10	0.166						
February	1.28	.021	1.31	.017	1.24	.107	1.32	.067	1.33	.142	1.48	.295						
March	2.11	.183	2.06	.162	2.00	.310	2.02	.221	1.98	.419	2.42	.623						
April	3.04	.155	2.99	.201	2.92	.620	2.92	.419	2.92	.715	2.97	.911						
May	5.21	.570	5.20	.727	5.16	1.418	5.23	1.255	5.60	2.034	5.76	2.588						
June	3.03	.319	2.98	.322	2.97	.702	2.92	.557	3.28	1.001	2.58	1.150						
July	2.53	.029	2.49	.038	2.40	.277	2.44	.190	2.13	.187	2.24	.444						
August	2.51	.003	2.48	.018	2.48	.228	2.42	.130	2.43	.312	2.12	.440						
September	3.74	.044	3.76	.056	3.71	.537	3.71	.354	3.25	.501	2.76	.469						
October	3.17	.189	3.11	.178	3.00	.696	2.99	.472	3.77	1.215	3.50	.984						
November	1.42	.089	1.42	.080	1.36	.272	1.38	.188	1.40	.397	1.55	.537						
December . . . . .	.97	.021	.95	.012	.93	.059	.95	.036	.96	.101	.63	.031					
Avg. ann. amt.	29.91	1.655	29.66	1.827	29.06	5.347	29.22	3.950	29.93	7.183	29.11	8.638						
Max. rain ³	9.58	1.094	9.42	.983	9.28	2.958	9.19	3.048	9.15	3.571	8.94	5.001						
Max. runoff ⁴	7.93	2.007	7.88	2.415	7.76	3.930	8.05	3.518	7.58	4.348	8.94	5.001						

¹Basic data are from USDA Miscellaneous Publications 1216, 1226, 1262, 1330, 1370, and 1380 (1965 through 1970).²Period of record: R-5 through R-8, July 1966 to July 1978; R-9, January 1971 to July 1978; R-10, May 1972 to July 1978.³High precipitation month: R-5 and R-6, October 1972; R-7 through R-10, May 1977.⁴High runoff month: R-1 through R-9, May 1973; R-10, May 1977.

Table 6-3.—Average monthly precipitation (*P*) and runoff (*Q*), in inches, for upland brush areas on fine sandy loam soils

Month	Watershed ¹					
	T-1 (42.6 acres)		T-2 (37.0 acre ^c)		T-3 (31.5 acres)	
	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>	<i>P</i>	<i>Q</i>
January	0.76	.00000	0.83	.00000	0.85	.00000
February	1.33	.00000	1.42	.00000	1.45	.00000
March	2.62	.00000	2.51	.0001	2.61	.00000
April	3.60	.0009	3.31	.00000	3.34	.0001
May	4.09	.0002	4.18	.0007	4.37	.0021
June	2.71	.0002	2.51	.0018	2.64	.0012
July	2.37	.0000	2.50	.0000	2.37	.0000
August	1.79	.0000	1.75	.0000	1.78	.0000
September	4.54	.0000	4.82	.0000	5.10	.0000
October	4.14	.0000	4.48	.0003	4.76	.0005
November	1.70	.0000	1.74	.0000	1.90	.0000
December . . . . .	.96	.0000	1.12	.0000	1.20	.0000
Avg. ann. amt.	30.61	.0013	31.17	.0029	32.37	.0039
Max. rain ²	8.87	.0000	9.40	.0016	10.20	.0003
Max. runoff ³	2.04	.0033	4.73	.0111	4.97	.0097

¹Period of record for all 3 watersheds was November 1968 to July 1974.

²High precipitation month for all 3 watersheds was October 1972.

³High runoff month: T-1, April 1972; T-2, June 1973; T-3, May, 1974.

vegetative cover, including standing material and mulch, accumulated. The total vegetative cover ranged from 0.5 to 2 tons per acre and averaged slightly more than 1 ton per acre for the period of record. In each watershed, the main drainageway was an incised, active gully.

The soils in R-7 and R-8 are a complex of Renfrow silt loam, Renfrow silt loam (severely eroded), Grant silt loam, and Kingfisher silt loam (eroded and severely eroded), with a permeability classification of moderate to slow.

Watershed R-7 was subdivided on January 1, 1971, with the upper portion being designated as watershed R-9. Data collection on R-9 was continued until July 1, 1978. This watershed had no active, incised gullies. However, prior erosion prevented the establishment of a good cover of desirable grasses on much of the area, with several spots remaining almost bare. A very small watershed of 1.48 acres, located adjacent to watershed R-8, was designated as R-10. This subwatershed was activated May 1, 1972, and data collection was continued until July 1, 1978.

Table 6-2 is a listing of period-of-record average monthly rainfall-runoff data. Runoffs from

R-5 and R-6 were about the same, which was expected because the soils, cover, and physical features of both watersheds were similar. However, they differed greatly from R-7 and R-8 in this respect. Runoffs from R-7 and R-8 were two to three times greater than those from R-5 or R-6. This difference was attributed to prior erosion and uncontrolled overgrazing. Runoffs from watersheds R-7 and R-9 were about the same for the R-9 period of record. Average annual runoff from R-9 was 7.18 inches compared to an annual average of 6.28 inches from R-7.

The average annual runoff of 8.64 inches from R-10 was greater than from all other unit-source areas, including 6.16 inches from R-7 for the R-10 period of record. This difference was primarily due to R-10 being much more severely eroded and having much less vegetative cover.

Available data from these watersheds include topographic and soil survey maps (Borgard et al. 1978), daily precipitation, runoff, sediment yield, periodic vegetative cover, and soil moisture. Precipitation intensities can be obtained from the rain-gage data charts.

UPLAND BRUSH OR BLACKJACK OAK AREAS

Three timbered upland watersheds (T-1 through T-3) were established November 1, 1968 and continued in operation until July 1, 1974. These watersheds range in size from about 32 acres to 43 acres and are located about 7 miles south and 6 miles west of Chickasha, Okla., in the Lake Burtschi area. The soils are in the Nash-Lucien-Stephenville association, a fine sandy loam with slopes of 3 to 8 percent.

Blackjack oak was the principal vegetative cover in these watersheds, with an understory of low-order shrubs, weeds, and grasses. The area produced very little grass and was used only very lightly for livestock grazing. The ground surface was generally a fluffy layer of forest litter, with an infiltration rate that was moderate to moderately rapid.

Table 6-3 summarizes the average monthly rainfall-runoff data from the timbered areas for the period of record. At the time these watersheds were instrumented, landowners were clearing this type of land to establish pasture. This was locally considered to be a desirable land-use change. The original intention of this research was to determine the hydrologic, erosion, and water-quality effects of changing land use from timber to pasture. This type of land, when cleared and planted to bermudagrass or weeping lovegrass, produces up to 4,500 pounds of forage per acre per year. Unfortunately, federal cost sharing funds were stopped, and neither federal research nor private funds were available to complete the land-use change portion of the research; therefore, data collection was terminated.

Available data include daily precipitation and runoff. Precipitation intensities can be determined from rain-gage data charts.

CULTIVATED BOTTOM-LAND AREAS

Eight cropland watersheds (C-1 through C-8), ranging in size from 12.75 to 44.26 acres, are located on Washita River alluvium. These watersheds, except C-2, were established January 1, 1965, and they continued in operation until January 1, 1977. Watershed C-2 was established May 1, 1962, and operation was discontinued July 1, 1974. The soils, all in land capability

class I, range from silt loam to silty clay loam, with a slope of zero to 1 percent.

In general, some surface land forming was required on all the watersheds to improve surface drainage. These watersheds were cropped as follows:

- C-1: Cotton (dryland).
- C-2: Alfalfa, cotton, sorghum (dryland).
- C-3: Cotton (supplemental irrigation).
- C-4: Cotton (supplemental irrigation).
- C-5: Wheat (dryland).
- C-6: Wheat (dryland).
- C-7: Alfalfa, cotton, sorghum (dryland).
- C-8: Wheat-alfalfa rotation (dryland).

Table 6-4 summarizes the average monthly rainfall-runoff data from the cropland watersheds for the period of record. Runoff from watershed C-2 was much less than from any of the other cropped areas. This watershed was on a coarser textured soil having good internal drainage. Watershed C-8, which was in an alfalfa-wheat rotation, produced less runoff than watersheds C-5 and C-6, which were in continuous wheat. Watershed C-1, which was in continuous dryland cotton, produced slightly more runoff than the two continuous-wheat watersheds but considerably less runoff than the two continuous-cotton watersheds (C-3 and C-4) with supplemental irrigation.

Available data from these watersheds include daily precipitation, runoff, sediment yield, periodic soil moisture, and topographic and soil survey maps. Precipitation intensities can be obtained from the rain-gage data charts.

SUMMARY

Runoff for 12 years from four formerly cultivated upland grassed watersheds (R-1 through R-4) on fine sandy loam soils ranged from an annual low of 0.068 inch to a high of 0.180 inch, with an average of only 0.108 inch.

Runoff for 12 years from watersheds R-5 and R-6, in native grass, averaged only 1.74 inches annually compared to an average of 4.65 inches from nearby watersheds R-7 and R-8, which had formerly been cultivated and later returned to native grass. Much of this difference was attributed to the loss of considerable amounts of topsoil from R-7 and R-8 and subsequent lesser amounts of vegetative cover resulting from un-

Table 6-4.—Average monthly precipitation (P) and runoff (Q), in inches, for bottom-land or alluvium cultivated watersheds

Month	Watershed ¹											
	C-1 (17.8 acres)		C-2 (32.5 acres)		C-3 (44.2 acres)		C-4 (29.9 acres)		C-5 (12.7 acres)		C-6 (13.0 acres)	
	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q
January	0.92	0.085	0.77	0.000	0.90	0.084	0.90	0.102	0.89	0.064	0.90	0.004
February	1.17	.004	1.01	.001	1.20	.024	1.18	.031	1.17	.097	1.17	.087
March	2.25	.159	1.85	.057	2.29	.174	2.29	.136	2.26	.351	2.26	.225
April	3.06	.170	2.85	.019	3.06	.394	3.04	.304	3.02	.223	3.03	.237
May	4.06	.440	3.68	.133	3.93	.847	3.92	.781	3.08	.415	3.80	.426
June	2.47	.193	2.91	.067	2.29	.413	2.30	.335	2.32	.169	2.32	.188
July	2.59	.427	1.80	.000	2.82	.630	2.79	.602	2.59	.183	2.59	.182
August	3.20	.271	2.49	.002	2.64	.409	2.67	.361	3.12	.045	3.12	.087
September	3.85	.267	3.56	.006	3.76	.434	3.76	.320	3.69	.163	3.69	.204
October	2.94	.398	2.29	.020	2.89	.496	2.89	.506	2.86	.359	2.85	.374
November	1.16	.178	1.64	.000	1.11	.078	1.09	.080	1.06	.044	1.06	.053
December . . . . .	.95	.045	.83	.000	.90	.018	.91	.011	.90	.001	.90	.007
Avg. ann. amt..	26.61	2.630	25.68	.305	27.74	4.011	26.15	3.348	27.68	2.124	27.69	2.316
Max. rain. ²	9.85	4.431	9.31	.368	9.94	4.530	9.82	4.455	9.87	1.620	9.90	1.426
Max. runoff ³	9.85	4.431	6.04	.859	9.94	4.530	9.82	4.455	6.35	2.578	6.36	2.792

¹Period of record: C-1, January 1965 to January 1977; C-2, May 1962 to July 1974; C-3 and C-4, September 1965 to January 1977; C-8, April 1965 to January 1977.

²High precipitation month: C-1 and C-3 through C-8, July 1975; C-2, June 1962.

³High runoff month: C-1, C-3, C-4, C-7, and C-8, July 1975; C-2, May 1974; C-5 and C-6, May 1973.

controlled overgrazing. Watershed R-9, which is a portion of watershed R-7, had an average annual runoff of 7.18 inches compared to 6.27 inches from R-7 for the R-9 period of record. Average annual Runoff from watershed R-10, a severely eroded and gullied area of only 1.48 acres, was 8.64 inches compared to 6.16 inches from watershed R-7 for the R-10 period of record.

There was essentially no measurable runoff from three timbered watersheds. There were plans for two of these areas to be cleared and established to grass, but because of insufficient funds they were not cleared.

Of the eight watersheds that were cropped, C-2 produced the least amount of runoff, probably because its soils were uniformly coarser textured

and thus more permeable. Watershed C-8, which was in a wheat-alfalfa rotation, produced less runoff than watersheds C-5 and C-6, which were in continuous wheat. The dryland-cotton watershed (C-1) produced slightly more runoff than the wheat areas but considerably less than the cotton areas having supplemental irrigation.

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Section 7.—Floodwater-Retarding Structures

INTRODUCTION

The Flood Control Act of 1944 authorized the Soil Conservation Service (SCS) to begin construction of floodwater-retarding structures on 11 watersheds in the United States. The program was broadened by the Watershed Protection and Flood Prevention Act of 1954 (Public Law 566). The first such reservoir in the country was completed and dedicated in the summer of 1948 in Washita County (near Cordell), Okla. Structure No. 1776 in Pontotoc County, Okla., was completed and dedicated in bicentennial year 1976.

The sizable agricultural lands subject to inundation, the wave-action erosion problem on some dams, the potential on-site water losses, and the irrigation potential of water stored in permanent pools prompted the initiation of research in the following areas:

1. Inundation tolerance of grasses.
2. Prediction of dam erosion by wave action.
3. Water budgets for selected impoundments.
4. Potential for irrigation with water from selected impoundments.

INUNDATION TOLERANCE OF GRASSES

Prolonged inundation of the detention pools in numerous reservoirs in Oklahoma, Texas, and Kansas killed hundreds of acres of native grasses during the spring and early summer of 1957. This created a need to better understand the flooding tolerance of grasses. A survey of 811 detention reservoirs in Oklahoma showed that there was an average of 91 acres of surface area in each detention pool subject to temporary inundation. This area, generally in range or pasture, serves as an important function in the production of livestock.

A review of literature revealed very little knowledge on the inundation tolerance of grasses. Therefore, a study of the inundation tolerance of numerous native and introduced grasses was conducted during 1961–65 (Rhoades 1964, 1967). Grasses were established in six basins, each ranging in depth from zero to 6 feet. The basins were flooded in early spring, mid-spring, and late spring for 5-, 10-, and 20-day periods. The grasses were classified according to their tolerance for flooding in central Oklahoma during early, mid, and late spring as follows:

Very strong for more than 20 days:

- Bermudagrass (*Cynodon dactylon*).
Buffalograss (*Buchloe dactyloides*).
Vine-mesquite (*Panicum Obtusum*).
Knotgrass (*Paspalum distichum*).

Strong for up to 20 days:

- Kanlow switchgrass (*Panicum virgatum* var.).
Lowland switchgrass (*Panicum virgatum* var.).
Reed canarygrass (*Phalaris arundinacea*).
Prairie cordgrass (*Spartina pectinata*).
Florida paspalum (*Paspalum floridanum*).

Moderately strong for up to 15 days:

- Caddo switchgrass (*Panicum virgatum* var.).
Upland switchgrass (*Panicum virgatum*).
Western wheatgrass (*Agropyron smithii*).
Rice cutgrass (*Leersia oryzoides*).
Smooth seed paspalum (*Paspalum pubiflorum*).

Moderate for up to 10 days:

- Big bluestem (*Andropogon gerardii*).
Sand bluestem (*Andropogon hallii*).
Virginia wildrye (*Elymus virginicus*).
Beaked panicum (*Panicum anceps*).

Mild for up to 5 days:

- Eastern gamagrass (*Tripsacum dactyloides*).
Alkali sacaton (*Sporobolus airoides*).
EI Kan bluestem (*Andropogon ischaemum* var.).
KR bluestem (*Andropogon ischaemum* var.).
Weeping lovegrass (*Eragrostis curvula*).
Kentucky fescue (*Festuca arundinacea* var.).
Little bluestem (*Andropogon scoparius*).
Indiangrass (*Sorghastrum nutans*).
Smooth brome (*Bromus inermis*).
Knotroot bristlegrass (*Setaria geniculata*).

PREDICTION OF DAM EROSION BY WAVE ACTION

After construction, some of the dams needed protection from damage by wave action. Such protection can be provided most efficiently at the time of construction if the need is known in advance. Therefore, a prediction technique was developed by applying discriminant analysis to site characteristics (DeCoursey 1973). This analysis was made by relating physical characteristics of the dam sites to their upstream slope stability. Physical characteristics included (1) the plasticity index of the soil material; (2) the fetch length, which is the length in miles of the water surface at normal pool level; (3) the water-surface area at normal pool level in acres; (4) the ratio of water-surface area to length; (5) the time-weighted velocity of all winds toward the dam but parallel to the direction of the fetch; (6) the time-weighted velocity of all winds normal to and into the face of the dam; and (7) the time-weighted velocity of wind only in the direction parallel to the fetch (for the 22.5° sector within which the fetch orientation falls). These variables were used to distinguish between the dams that needed to have slope protection installed at the time of construction and those that did not. Twenty-five sites that required slope protection and twenty-five sites that did not require it were selected for use in the analysis.

The most important single discriminator was the average width of the lake surface. As the width increased, the possibility for erosion of the slope increased because there was more opportunity for wind to produce large waves from directions other than that of the fetch. The second most important variable was the length of the fetch. As the length of fetch increased, the likelihood of higher waves and greater damage increased. The third and last factor of significance was the soil plasticity index. Erosion of cohesive soils is much slower than the erosion of non-cohesive soils. The discrimination procedure was then used to assign other sites to one of the two categories (slope protection needed or not needed) on the basis of the three significant site characteristics. Fifteen independent test sites were assigned with about a 20-percent error in classification, which was deemed reasonable accuracy.

Different plans of providing protection were compared. The cost of initially providing protec-

tion to all sites, whether needed or not, was used as a base and assigned a cost value of 10 units. An analysis of discriminant scores of structures needing and not needing slope protection gave a cost comparison of four plans, as summarized in the following tabulation:

Plan	Relative cost
Protection for all sites	10.0
All protection as needed	5.9
Minimum cost using discrimination	4.7
95-percent of needed protection at time of construction	6.4

WATER BUDGETS FOR SELECTED IMPOUNDMENTS

Depletion of water from impoundments may be an important economic consideration in areas where water supplies are limited. Therefore, the water budgets of selected impoundments on Sugar Creek and Winter Creek were studied to determine the on-site water loss by evapotranspiration and seepage from the impoundments (Schoof and Naney 1976, Schoof et al. 1980).

The instrumentation necessary for computation of impoundment water budgets is as follows: (1) a recording rain gage, (2) a surface-water-level recorder on the impoundment, (3) a low-flow weir and a surface-water-level recorder for each inflow channel that has significant base flow, and (4) a low-flow outflow weir and water-level recorder if the water level-discharge relation for the principal spillway is insensitive (i.e., a small change in water level causes a large change in discharge).

A computerized procedure was developed to compute the impoundment water budgets. A listing of computer output for each period of 1 or more days of surface inflow to the impoundment included impoundment and watershed numbers, year, month, day, time, gage height, rainfall on the pool, volume of water stored in the pool, rate of flow from the principal spillway, accumulated principal-spillway discharge, rate of inflow, and accumulated inflow. The daily summaries were held in computer storage. The daily, monthly, and annual summaries were then listed at the end of a station-year of computation (Schoof 1977).

Analysis of the water budgets for three Sugar Creek impoundments (table 7-1) indicates that little water flowed past the dams in years with less-than-normal precipitation. (See fig. 2-1 for

Table 7-1.—Annual water budgets (acre-feet) of three Sugar Creek floodwater-retarding impoundments

Year	Inflow		Rain on pool	Outflow		Change in volume	Evaporation and seepage
	Surface	Base		Principal spillway	Other release		
SITE 13							
1964	79	0	32	0	.....	48	63
1965	317	0	46	189	.....	74	100
1966	62	0	32	13	.....	-12	93
1967	19	0	31	0	.....	-33	83
1968	150	11	52	85	.....	51	77
1969	64	14	35	71	.....	-36	78
1970	19	0	17	0	16	-50	70
1971	71	2	26	0	.....	37	62
1972	4	0	12	0	.....	-38	54
1973	88	0	43	0	.....	58	73
1974	86	0	44	28	.....	27	75
Average . . .	87	2	34	35	1	12	75
SITE 15 ²							
1968	82	0	28	0	.....	34	76
1969	61	0	23	0	16	-25	93
1970	39	0	10	0	.....	-16	65
1971	*	*	*	*	*	*	*
1972	*	*	*	*	*	*	*
1973	54	0	19	0	7	10	56
Average . . .	59	0	20	0	6	1	72
SITE 25							
1969	128	10	52	0	.....	80	110
1970	31	0	23	0	120	-131	65
1971	39	0	25	0	.....	5	59
1972	6	0	8	0	.....	-28	42
1973	161	0	48	0	.....	128	81
1974	120	0	66	0	.....	74	122
Average . . .	82	2	37	0	20	21	80

¹Release of water for dam repair.

²Asterisk indicates water level too low to obtain a complete record.

³Release of water for irrigation.

⁴Release of water for irrigation and dam repair.

locations of impoundment sites.) Runoff depletion at the three sites was similar to that for floodwater-retarding impoundments in Texas and Oklahoma (Sauer and Masch 1969). The average annual evaporation and seepage at two of the Sugar Creek sites (13 and 25) was 62 inches. However, the third site (15) had an average annual evaporation and seepage loss of 95 inches. Some of the depletion there was attributed to pumpage from nearby irrigation wells. Seepage

into the alluvium downstream from the dams accounted for 7.1 to 15.6 percent of the combined evaporation and seepage from the three impoundments. Our recommendation was to include multiple ports in the risers of future structures so that maximum storage in the permanent pools could be regulated as the pools fill with sediment.

The average annual evaporation and seepage loss from site 7 on Winter Creek in years with less-than-average rainfall was 46 acre-feet or 67

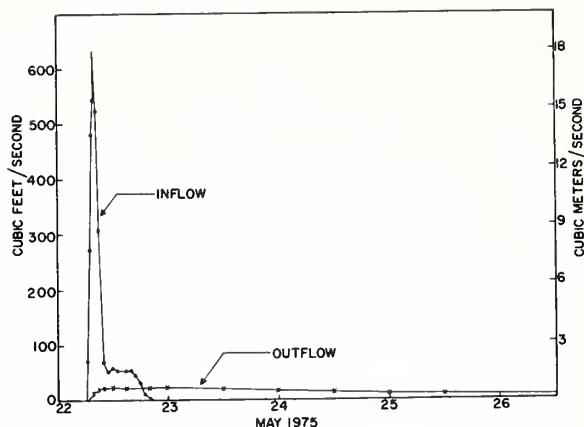


FIGURE 7-1.—Inflow and outflow hydrographs for runoff event of May 22, 1975 at site 7 on Winter Creek.

inches, which was about 40 percent of the combined inflow and rainfall on the pool during the 4 years of records. The drainage area into the structure is 657 acres, and the permanent pool stores 53 acre-feet. During the wet years of 1973 and 1975, there was unmeasured seepage into the pool, which was computed as a negative loss that made the water budgets for those years inaccurate (Schoof et al. 1980).

The inflow and outflow hydrographs for a runoff event at site 7 on May 22, 1975 are shown in figure 7-1. The peak inflow was reduced in passing through the structure, so its contribution was insignificant to the peak flow downstream as water was slowly released for several days.

POTENTIAL FOR IRRIGATION

Droughts occur frequently during the summer growing season in western Oklahoma and sometimes the results are stressed crops and reduced production. Table 7-2 shows the probability of various amounts of precipitation occurring during each month at Fort Sill, Okla. The data were computed from a 100-year precipitation record.

The possibility of the waste of a valuable resource, water stored in the permanent pools, prompted research on the potential for using this water for irrigation. To determine the potential for irrigating with water from the SCS floodwater-retarding impoundments, the following four questions were addressed: (1) What is

the present extent of irrigation from the impoundments? (2) What is the irrigation-water storage potential of the impoundments within the Washita River basin between Anadarko and Alex? (3) Does a farmer need a legal water right to use water from the impoundments, and if so, how is it obtained? (4) If water is released from an impoundment and permitted to flow downstream to a point of use, what is the transmission loss from the flow?

A survey of the Washita study reach in 1977 disclosed that irrigation water was withdrawn from only 2 impoundments on West Bitter Creek and 14 impoundments on Sugar Creek. A total of 1,058 acres were irrigated from the 16 sites. The principal crop under irrigation was peanuts. A small amount of water was applied to soybeans, cotton, watermelons, alfalfa, bermudagrass, and corn. The total amount of water applied was less than 500 acre-feet. Within the 1,130-square-mile study reach, there were 136 completed floodwater-retarding impoundments on January 1, 1978. Those impoundments had more than 13,000 acre-feet of potential water storage in the sediment pools. Thus, very little of the potential was being used for irrigation.

The owners of floodwater-retarding impoundments can obtain legal rights to the use of water stored in the sediment pools. Application must be filed with the Oklahoma Water Resources Board. A landowner must own part of the flood pool, dam, spillway, or sediment pool to obtain the legal right to use part of the water.

Two tests were conducted to determine the transmission loss from water released from impoundments on East Bitter and Winter Creeks (Schoof and Price 1980). During the first week of August 1976, water was released from site 7 on Winter Creek. Seventy-five percent of the water reached the Winter Creek gaging station 6 miles downstream. The base flow at the gaging station before the release was slightly greater than 1 cubic foot per second. The results of a test on East Bitter Creek were not so good. Water was released from site 17 for 7 days, August 16–23, 1976. A total release of 10.3 acre-feet was made, but only 44 percent of the water reached the East Bitter Creek gaging station 4.5 miles downstream. Base flow at the gaging station was 0.53 cubic foot per second. The flow was impeded by beaver dams in a one-fourth-mile reach of the creek.

Table 7-2.—Monthly precipitation probabilities based on a 100-year record at Fort Sill, Okla.

Precipitation (inches)	Probability (percent) for month of —											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1.0	51	55	69	82	96	90	76	76	82	75	59	59
2.0	17	25	36	59	87	73	52	58	62	54	31	32
4.0	3	2	3	25	59	36	24	18	33	29	11	5
6.0	0	0	1	8	31	14	7	8	12	12	4	0
8.0	0	0	0	2	15	6	2	2	5	8	0	0

SUMMARY

Generally, grasses can withstand longer periods of inundation when dormant and while the air and water are relatively cool. When plants are actively growing, severity of injury depends upon their stage of growth and time of year when flooded. In this study, damage to plants increased as the depth or duration of flooding increased, but no attempt was made to determine the specific cause of damage or death. A review of literature indicates that one cause is the imbalance of oxygen-carbon dioxide in the root zone.

Discriminant analysis was used to analyze factors related to the adequacy of standard slope protection on small dams. The structures were divided into two groups—one group that needed additional slope protection and one group that had been designed satisfactorily. The analysis showed that a linear combination of the fetch length, the ratio of surface area to length (average width), and the plasticity index of the surface material on the dam could be used to distinguish between the two groups about 85 percent of the time. The equation defined by these parameters was scaled for cost and number of structures and can be used to assign structures to the two groups so that additional protection can be most economically provided.

A computer program for computing impoundment water budgets was developed and applied to records collected at three sites on Sugar Creek and one site on Winter Creek. The water budgets for the Sugar Creek impoundments showed that little water had flowed past the structures in years with less-than-normal precipitation. Runoff depletion at the three sites was similar to that for floodwater-retarding impoundments in Texas and Oklahoma (Sauer and Masch 1969). During years with less-than-average precipitation at site 7 on Winter Creek, the average annual evaporation

and seepage was 46 acre-feet or about 40 percent of the combined inflow and rainfall on the pool.

A study was conducted to determine the feasibility of irrigating with water stored in the sediment pools of floodwater-retarding impoundments within the 1,130-square-mile study reach. In 1977, less than 600 acre-feet of water from these impoundments were used for irrigating less than 2 square miles of land. There is a potential for much greater use of this water for irrigation, and the associated engineering problems can be solved. Although no study of the economics was made, the primary constraint appears to be an unfavorable benefit-cost relation.

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Section 8.—Treatment Effects and Runoff Characteristics of Large Watersheds

INTRODUCTION

The objectives of this research were to relate runoff to its causative factors and to assess the effect of the Soil Conservation Service (SCS) flood-control program on the downstream flow regime of the Washita River. The objectives included specific objectives as follows: (1) identify and evaluate the factors affecting storm runoff and water yield; (2) determine the changes in storm runoff, water yield, and flow duration caused by watershed conservation improvements; (3) determine the extent of transmission losses and gains in the Washita River and its

tributaries; and (4) develop procedures for estimating flow from ungaged watersheds.

The need for this research was recognized during the 1952-56 drouth in the Great Plains. Construction of floodwater-retarding impoundments by SCS on the Washita River watershed began about 1947, and many downstream water users felt that the impoundments might deplete their dwindling water supply.

To determine the effect of the treatments on the downstream flow regime, runoff records were collected at 6 Washita River and 15 tributary stations (fig. 2-1 and table 8-1). The effects of the treatments on downstream water yield, flow duration, peak flows, and transmission losses are discussed in this section. Some of the flow characteristics, including flood frequency, flow duration, and minimum flow for selected time periods, are also discussed.

Table 8-1.—Drainage areas and years of record at Washita River and major tributary watersheds

Watershed	Test station number	Drainage area (mi ²)	Years of record
Washita River:			
At Anadarko	100	3,656.0	1961-78
At Verden	200	4,082.0	1961-74
Near Chickasha	400	4,259.0	1961-66
Near Chickasha	500	4,325.0	1964-77
Near Tabler	600	4,706.0	1963-70
At Alex	700	4,783.0	1961-78
Tonkawa Creek	110	39.1	1963-77
Tonkawa Creek	111	26.0	1962-77
Sugar Creek	121	205.9	1955-74
Delaware Creek	131	40.1	1962-77
Salt Creek	311	23.76	1966-77
Line Creek	411	52.0	1962-74
West Bitter Creek	511	59.4	1962-77
East Bitter Creek	512	207.8	1963-77
East Bitter Creek	513	19.24	1964-77
West Bitter Creek	515	2.589	1972-78
Little Washita River	522	207.8	1951-78
Little Washita River	526	61.9	1979-78
Dry Creek	611	7.57	1961-74
Little Dry Creek	612	.88	1961-74
Winter Creek	621	33.3	1962-78

IMPACT OF IMPOUNDMENTS AND CHANNEL DREDGING

Water yield.—In 1957, the Agricultural Research Service (ARS), SCS, and the U.S. Bureau of Reclamation established an interagency work group to conduct a 5-year study of procedures for assessing the influences of watershed treatment on downstream water yield. A “rational method” for assessment was developed, but no significant conclusions were reached (A. L. Sharp et al., unpublished data). The general consensus was that the existing hydrologic records were not sufficiently accurate to define the effects of land treatment and reservoirs on downstream water yield.

Kennon (1966) reported that Sandstone Creek, a tributary to the Washita River in Cheyenne County, Okla., had changed from an ephemeral to a perennial stream as a result of seepage from

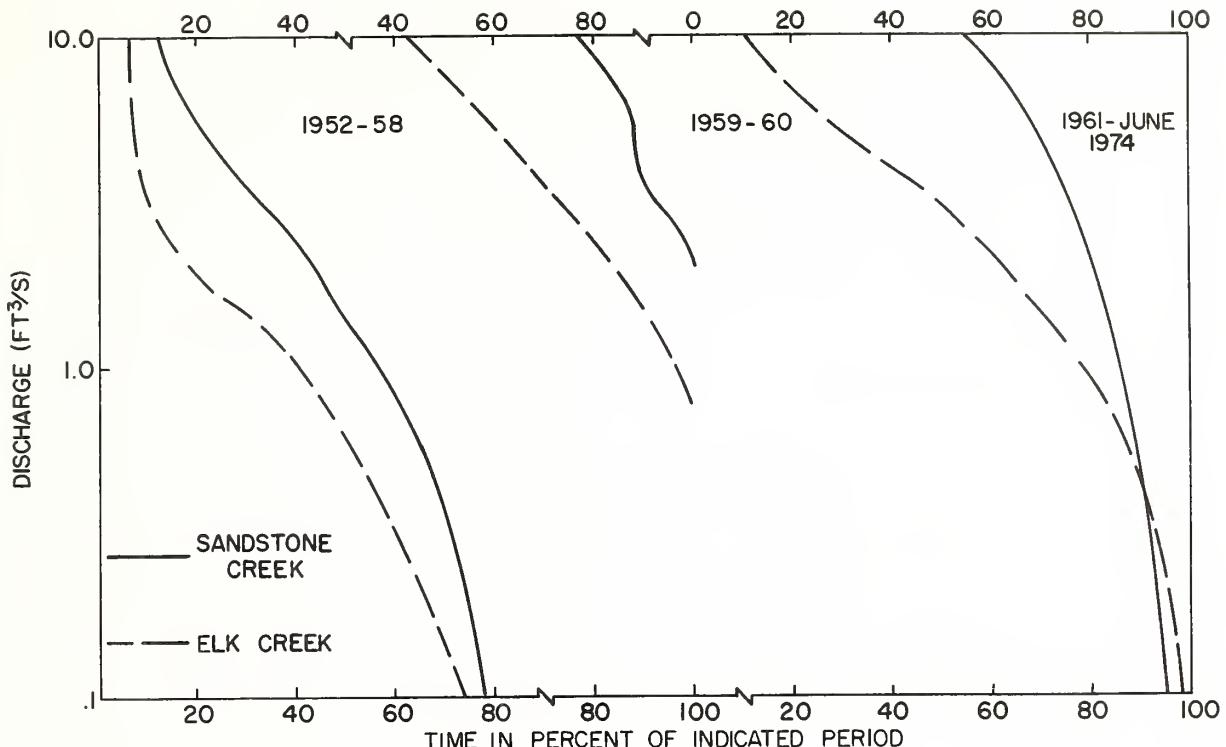


FIGURE 8-1.—Flow-duration curves for Sandstone Creek and Elk Creek before, during, and after installation of floodwater-retarding structures on Sandstone Creek.

floodwater-retarding structures. However, his analysis was based on records collected in 1960-61 when rainfall was considerably above the long-term average. Comparison of the Sandstone Creek runoff record with the runoff record from an adjacent untreated watershed (fig. 8-1) does not support Kennon's conclusions. The average annual precipitation, in inches, for each watershed for periods before, during, and after installation of floodwater-retarding structures on Sandstone Creek is shown below.

Period	Average annual precipitation		Precipitation ratio
	Elk Creek	Sandstone Creek	
1952-1958	21.29	20.70	0.97
1959-1960	33.70	35.22	1.04
1961-June 1974	22.84	23.65	1.03

Beard and Moore (1976) reported an increase in water yield ranging from 1 to 30 percent following installation of floodwater-retarding structures on Little Elm Creek watershed in central Texas. These results were the opposite of what is

normally expected, but the authors had no explanation for them. They also noted that in the low-flow condition, monthly runoff decreased after the structures were installed.

During the first 5 years of the Washita research project, the 1941-50 hydrologic records of the Washita River and its tributaries were studied to determine the effects of a superimposed flood-prevention program on the downstream flow regime. For that period of greater than normal rainfall, the computed reduction in yield ranged from about 16 percent in the upstream reaches to about 2 percent in the downstream reaches (Decoursey 1975).

About 1970, a study was made of the effects of floodwater-retarding structures on the water yield of Rush Creek, a Washita River tributary adjacent to the study reach (R. R. Schoof, unpublished data). A modified version of the SCS runoff model was fitted to the pretreatment runoff record and was then used to simulate runoff for the posttreatment period as though the structures were not in place. During the post-treatment period, structures controlled runoff

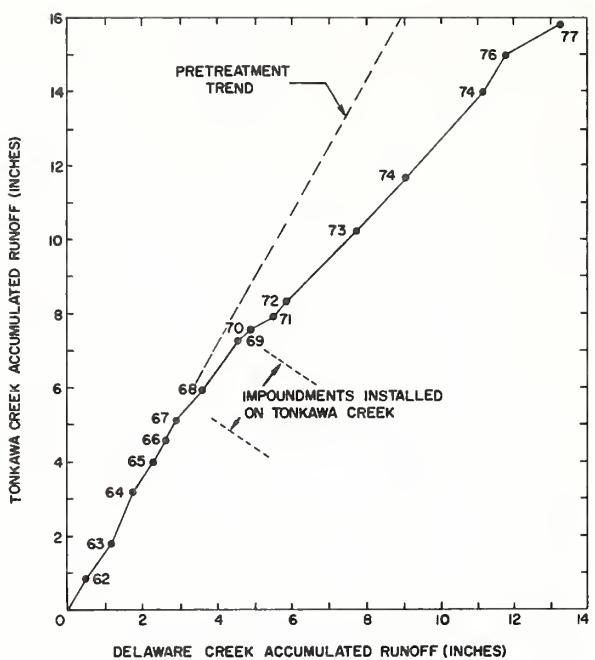


FIGURE 8-2.—Double-mass runoff of Delaware Creek (untreated) versus Tonkawa Creek (treated with flood-control structures).

from 22 to 46 percent of the 206-square-mile watershed, and the average annual rainfall was 32.5 inches. Later, two other models were applied to the same record (E. H. Seely, unpublished data). Comparison of the runoff simulated by the three models with measured runoff indicated that the structures had decreased the runoff 24, 27, and 29 percent.

A double-mass analysis of runoff from the Washita River at Durwood, Okla., and the untreated Kiamichi River at Belzoni, Okla., was made for the period 1929-64 by Hartman et al. (1966). They concluded that the plotting showed no change in the runoff relationship between the two watersheds. The double-mass relationship was extended through 1971 by Seely (1976). The extended analysis suggested that a change might have occurred, beginning about 1963 when SCS structures controlled runoff from nearly 25 percent of the Washita River basin. The U.S. Bureau of Reclamation Reservoirs at Foss, Okla., and Fort Cobb, Okla., were also in place then. Seely concluded that the observed difference could not be explained by the SCS structures alone, since it was several times greater than any reasonable estimate. The great decrease in flow of the Washita River as compared to that of the Kiamichi River could probably be explained by

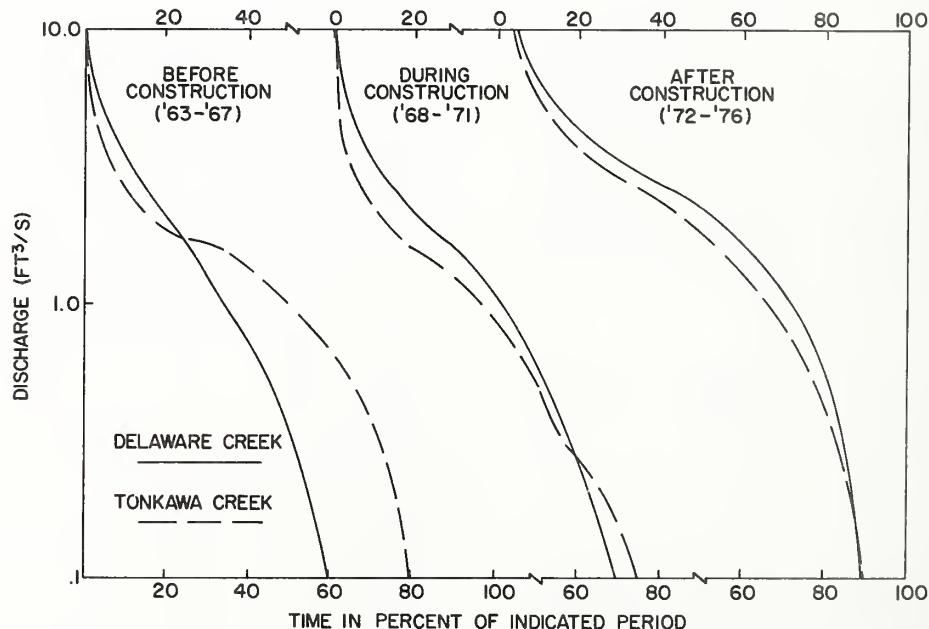


FIGURE 8-3.—Flow-duration curves for Tonkawa Creek and Delaware Creek before, during, and after installation of floodwater-retarding structures on Tonkawa Creek.

the severe drought of the 1960's on the Washita River watershed. Seely also compared runoff from the Washita River with that from the Red River near Gainesville, Tex., where little structural treatment was in place, and found no significant change.

Floodwater-retarding structures, controlling 68 percent of the drainage area upstream from Tonkawa Creek station 111 (fig. 2-1), were installed from 1968 to 1970. Double-mass comparison of Tonkawa Creek runoff with that from the adjacent untreated Delaware Creek indicates that, during the 5 years after the impoundments were filled, the volume of flow at station 111 was reduced 36 percent, as shown in figure 8-2 (Schoof et al. 1978). During the posttreatment period, the annual precipitation averaged 5 to 6 inches more than during the pretreatment period. Therefore, the runoff relationship between these watersheds may have changed because of the climatic change. A flow-duration relationship for the two watersheds (fig. 8-3) shows that the flow reduction on Tonkawa Creek was predominately in the low-flow range. However, some of this apparent flow reduction may have been the result of greater timber removal from Delaware Creek than from Tonkawa Creek, as shown in table 2-6.

In 1974, structures controlled runoff from 23 percent of the Little Washita watershed, and in 1977 the control was 44 percent. A double-mass comparison of runoff from the untreated Delaware Creek watershed and the Little Washita River watershed can be made from figure 8-4. A straight line fits the data for the entire period. A double-mass comparison of runoff from the Little Washita River with runoff from adjacent, untreated Beaver Creek also does not show any change in the water yield of the Little Washita River. Thus, there appears to be no effect of the structures on the water yield of this river. The Little Washita River is also one of the three tributaries within the study reach where there was apparently no reduction in sediment yield following structural treatment (see section 10). Currently, no reason can be given for this anomalous finding.

A straight line also fits the double-mass plot of runoff for untreated Delaware Creek and the entire 1,130-square-mile study reach, as shown in figure 8-5. Thus, any reduction of runoff caused by structures within the study reach apparently was offset by increased runoff from Sugar and Tonkawa Creeks, which were dredged in about

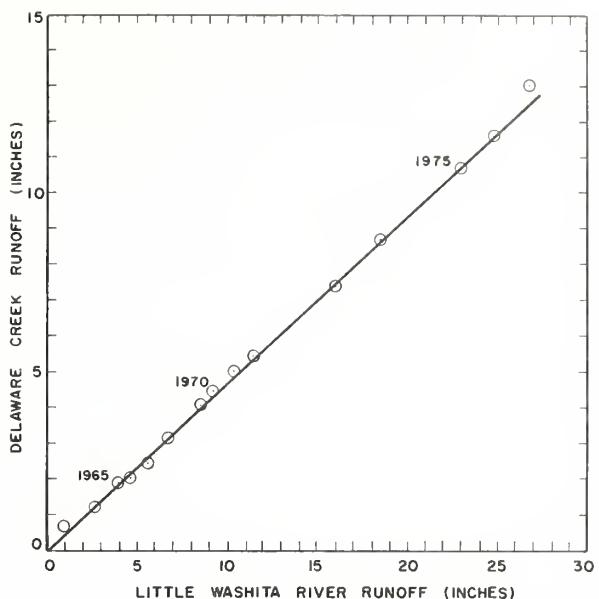


FIGURE 8-4.—Double-mass runoff of Delaware Creek (untreated) versus Little Washita River (treated with flood-control structures).

1967 and 1973, respectively. A double-mass comparison of runoff from the Tonkawa and Delaware Creek watersheds (fig. 8-6) shows that channel dredging increased the water yield of Tonkawa Creek about 400 percent.

Flood peaks.—Flow of floodwater through an emergency spillway is an extremely rare event, and flow through the principal spillways is an insignificant addition to the peak flow downstream. Therefore, on Sugar and Winter Creeks the peak flow at a point downstream is reduced by a percentage equal to the percentage of the drainage area controlled by the structures (Hartman et al. 1967, Schoof et al. 1980). This relationship may not hold true for all watersheds, however.

A flood-frequency study on Winter Creek (Schoof et al. 1980) indicated that a peak discharge occurring on the average every 2 years before structural treatment would occur on the average every 5 years following treatment. Similarly, a pretreatment peak discharge occurring on the average every 10 years would occur on the average about every 100 years after treatment. The structures decrease high flows and increase intermediate flows. In areas of low rainfall where there is little flow through the spillways, a structural program would probably reduce the

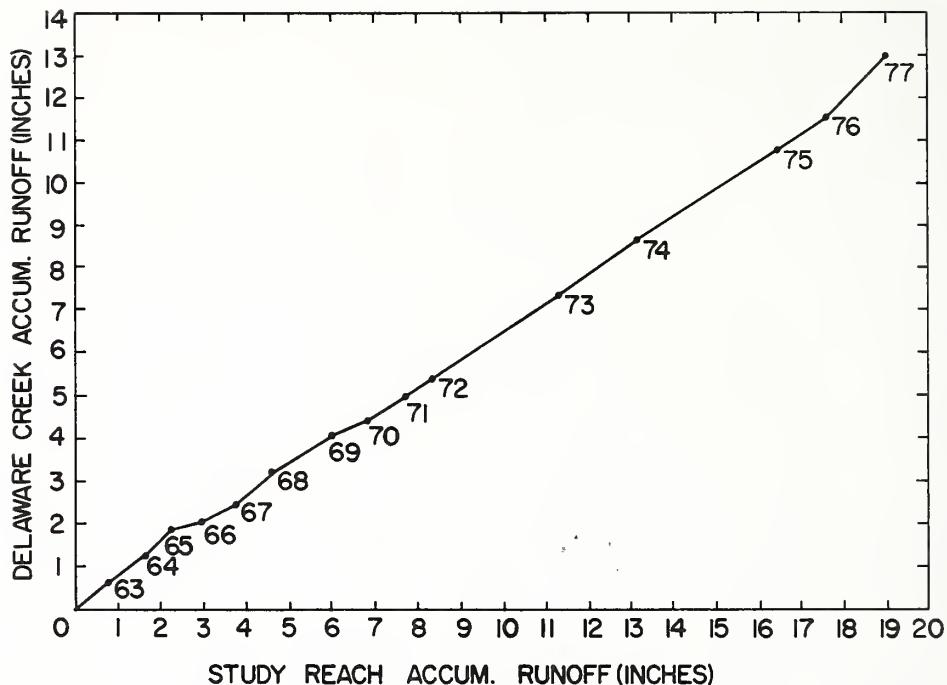


FIGURE 8-5.—Double-mass runoff of Delaware Creek (untreated) versus Washita study reach (partially treated with flood-control structures).

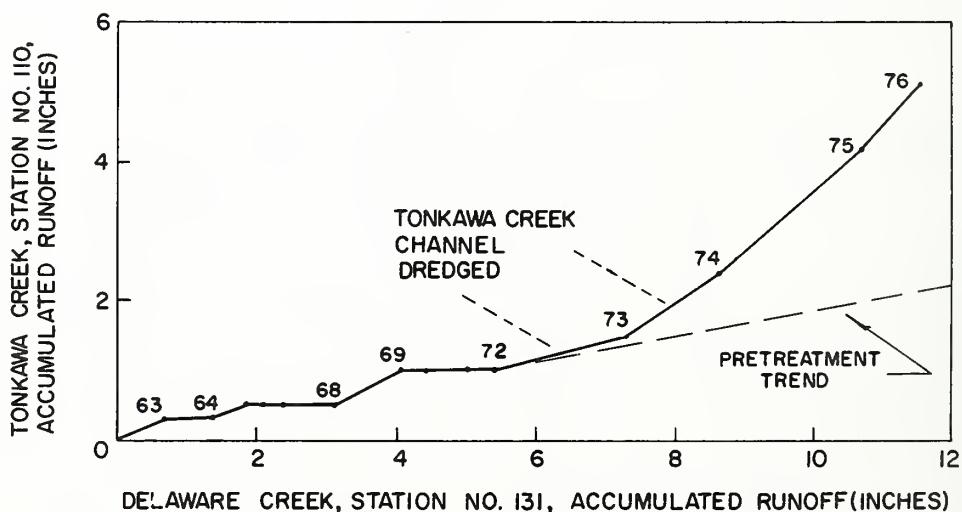


FIGURE 8-6.—Double-mass runoff of Delaware Creek (untreated) versus Tonkawa Creek (treated by dredging channel).

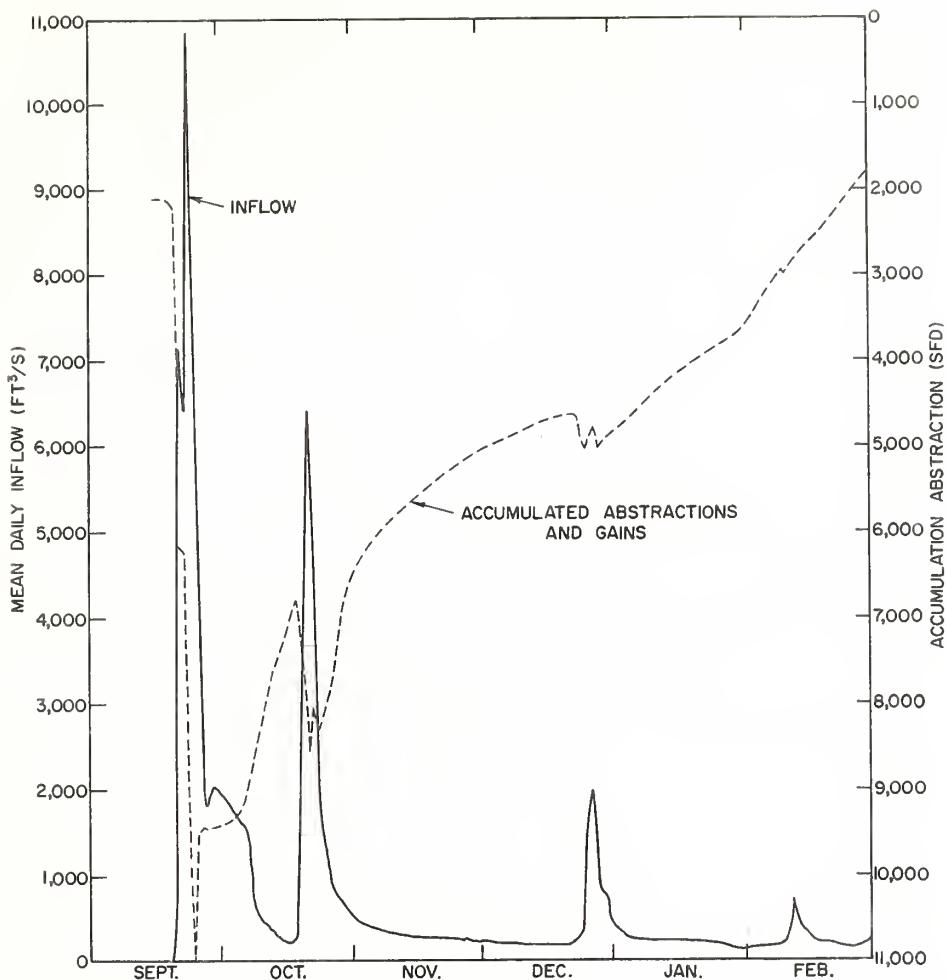


FIGURE 8-7.—Mean daily inflow and accumulated abstractions and gains for selected events on Anadarko-Verden reach in 1965. SFD, second-foot-day, is the volume represented by 1 cubic foot per second flowing for 24 hours.

base flow downstream (Schoof et al. 1978, Beard and Moore 1976).

Transmission losses.—The effect of floodwater-retarding impoundments on transmission losses from the Washita River tributaries could not be assessed because the local inflow between tandem gaging stations was not determined. However, Schoof et al. (1967) determined the transmission losses for selected runoff events through the Anadarko-Verden reach of the Washita River. There was a subsequent recovery of flow loss from runoff events in the dormant season, but losses were not recovered from storm events during the growing season. Sufficient runoff records were not available to successfully relate the storm-flow loss to antecedent conditions.

The September 1965 runoff event (fig. 8-7) in-

undated about 3,400 acres along the 10 miles of Sugar Creek channel below the gaging station (figure 2-1). An additional 2,300 acres of cropland and 350 acres of timberland were inundated along the Washita River. The water infiltrated the inundated area along Sugar Creek for an average of 24 hours and the inundated area along the Washita River for an average of 72 hours. As a result, there were 279,000 acre-hours of flood plain infiltration at an average rate of 0.79 inch per hour. The flow abstraction between Anadarko and Verden (22 river-miles) during the 11-day runoff event was about 14 percent of the total inflow. However, the abstraction was fully recovered as a result of increased base flow during the next 5 months. About 9.5 percent of the runoff that

(Continued on page 84.)

Table 8-2.—Annual precipitation (P) and runoff (Q),

	Tonkawa 110	Tonkawa 111	Sugar 121	Delaware 131	Ungaged area 100-200	Reach 100-200	Salt 311	Line 411	Ungaged area 200-500	Reach 200-500
1962)P)Q			26.28 1.061							
1963)P)Q		17.07 .984	25.22 .521	18.99 .670				19.04 .392		
1964)P)Q	30.80 .129	31.56 1.378	25.47 .355	31.91 .603	1.619	27.26 .508		29.06 .466	-.390	29.50 -.207
1965)P)Q	20.95 .137	20.85 .860	32.02 2.163	24.22 .577	-.909	28.61 .937		23.93 .449	-1.787	24.08 -1.309
1966)P)Q	20.10 .000	19.73 .543	21.33 .612	20.18 .243	3.008	21.29 .817		20.77 .069	.448	20.87 .367
1967)P)Q	24.55 .000	24.39 .537	24.87 .593	26.53 .303	1.040	25.54 .483	27.84 2.317	25.41 .326	.797	27.32 .845
1968)P)Q	32.30 .000	33.28 .826	36.50 1.367	33.94 .723	1.233	34.47 .923	29.09 .613	30.17 .076	-.301	30.63 -.130
1969)P)Q	24.32 .484	24.59 1.283	27.57 2.018	25.76 .953	-.272	27.85 1.068	27.86 2.541	24.41 .552	1.065	26.71 1.100
1970)P)Q	22.06 .006	21.14 .325	19.76 .725	21.66 .332	-.558	21.40 .295	25.81 2.098	21.52 .185	1.434	24.57 1.232
1971)P)Q	30.39 .009	30.75 .270	27.83 .370	30.92 .585	-.111	28.27 .390	30.59 2.052	29.38 .905	1.245	30.50 1.251
1972)P)Q	23.28 .004	23.78 .476	18.06 .151	23.93 .429	-.424	19.66 .053	19.94 .320	24.53 .454	.212	21.79 .275
1973)P)Q	39.47 .469	38.93 1.917	38.69 1.494	40.36 1.923	-.863	38.45 .826	35.99 3.153	39.11 1.658	2.867	37.79 2.636
1974)P)Q	30.93 .920	31.16 1.483		31.61 1.319		32.08 1.043	32.78 3.293			31.48 2.370
1975)P)Q	34.27 1.786	34.31 2.344		35.07 2.072			33.34 4.179			
1976)P)Q	24.91 .929	24.65 1.372		23.27 .826			20.22 .679			
1977)P)Q	23.74 .387	23.44 .787		28.05 1.460			28.22 1.754			
Avg.)P)Q	27.29 .376	26.64 1.026	26.97 .952	27.76 .868		27.72 .668	28.34 2.091	26.12 .503		27.75 .766
%	1.38	3.85	3.53	3.13		2.41	7.38	1.93		2.76

in inches, for Washita River and tributary watersheds

West Bitter 511	East Bitter 512	East Bitter 513	Little Washita 522	Dry 611	Dry 612	Winter 621	Ungaged area 500-700	Reach 500-700	Study reach 100-700
				26.65 2.324	28.39 4.471				28.47 1.923
20.37 1.159				17.90 1.053	18.96 1.323	19.35 1.986			19.91 .827
28.91 1.010	33.29 2.394		30.84 1.696	31.68 1.973	29.61 .536	33.09 2.883	1.468	31.00 1.692	28.76 .835
24.35 1.263	25.29 2.147	24.29 2.151	25.70 1.247	22.14 .310	24.04 .084	27.38 2.373	1.071	25.44 1.338	26.41 .616
24.00 1.591	24.69 1.879	25.16 2.124	19.60 .659	24.29 .639	24.74 .312	22.14 1.387	.086	21.80 .783	21.72 .706
27.27 1.584	28.14 1.853	28.56 2.355	26.33 .685	24.81 .302	25.53 .355	27.21 1.519	1.122	26.62 1.054	26.41 .793
30.48 .888	31.96 1.426	30.92 1.278	34.02 1.386	34.90 1.629	35.06 .890	33.96 2.475	.609	33.31 1.213	33.12 .814
28.02 2.203	29.02 3.031	29.46 3.296	28.03 1.844	26.58 2.640	24.72 .857	30.41 3.708	1.143	27.50 1.955	27.46 1.435
25.61 1.757	26.18 1.557	26.48 1.581	21.14 .696	25.91 1.826	26.44 .908	28.02 3.006	.911	33.50 1.140	23.10 .840
31.85 2.246	34.25 2.566	34.99 2.488	31.30 1.164	31.69 1.340	31.47 1.225	32.27 2.829	.364	32.27 1.336	30.73 .895
24.60 1.315	25.87 1.914	26.37 2.125	26.06 1.102	25.66 2.886	25.77 1.057	26.63 3.015	1.171	26.02 1.378	22.65 .639
47.27 7.236	46.50 9.951	47.41 10.830	45.03 4.506	43.27 7.720	42.34 3.334	42.96 8.321	1.994	43.80 4.983	40.49 2.906
31.67 3.883	30.82 3.467	30.85 4.000	31.69 2.537	31.79 3.890	29.34 1.226	29.45 3.854		31.16 2.327	31.53 1.847
33.31 6.122	33.50 6.193	34.92 6.878	36.74 4.443			31.71 6.149			34.89 3.333
21.11 1.009	22.34 1.392	22.23 1.389	24.24 1.763			24.34 1.845			23.23 1.131
23.36 1.456	24.04 1.717	23.74 1.770	29.70 2.020			23.92 1.863			23.37 1.329
27.81 2.315	29.71 2.963	29.65 3.251	29.32 1.839	28.25 2.195	28.19 1.275	28.86 3.148		30.22 1.745	27.64 1.304
8.32	9.97	10.96	6.27	7.77	4.52	10.91		5.77	4.72

Table 8-3.—Annual peak discharge (Q), in cubic feet per second, and gage

		Washita 100	Tonkawa 110	Tonkawa 111	Sugar 121	Delaware 131	Washita 200	Salt 311	Washita 400	Line 411
1962	Q G.Ht.	5,230 17.97			1,260 8.00		5,170 25.40		6,200 26.20	
1963	Q G.Ht.	2,980 12.92	7.4 7.15	137 9.09	910 8.59	177 11.55	2,750 18.18		2,510 17.81	408 14.46
1964	Q G.Ht.	5,050 17.17	89 8.18	772 5.75	801 8.75	430 5.04	4,950 23.72		4,410 22.70	403 15.10
1965	Q G.Ht.	11,000 24.20	36 7.75	346 4.33	8,500 10.77	459 5.03	8,410 27.93		6,900 26.33	2,010 19.45
1966	Q G.Ht.	1,230 10.07	2.7 6.05	80 2.99	790 7.45	61 2.94	1,260 14.43		1,960 16.56	92 12.92
1967	Q G.Ht.	2,470 12.91	No Flow	639 5.12	5,430 16.85	340 4.62	2,470 18.07	4,900 16.10		869 17.23
1968	Q G.Ht.	3,840 15.65	No Flow	284 4.17	2,400 11.60	733 7.25	3,890 21.28	348 8.04		135 13.68
1969	Q G.Ht.	5,650 18.61	79 9.61	538 5.10	4,640 14.41	555 6.01	5,470 25.17	1,150 13.27		440 20.42
1970	Q G.Ht.	1,470 9.69	14.2 6.84	101 3.13	2,990 8.54	171 3.82	1,740 16.87	1,370 14.03		110 15.34
1971	Q G.Ht.	2,080 12.46	22.9 7.60	400 4.58	534 7.31	602 6.57	1,910 18.75	859 10.00		1,210 17.49
1972	Q G.Ht.	1,140 9.36	7.7 6.38	355 4.40	173 6.57	119 3.42	1,080 15.73	278 6.27		477 19.29
1973	Q G.Ht.	4,700 18.02	46 8.25	317 4.24	1,070 7.43	1,080 10.47	4,340 26.10	925 10.38		832 21.76
1974	Q G.Ht.	3,100 15.05	36 7.71	216 3.75	831 6.50	272 5.45	3,260 23.27	1,150 11.58		741 20.27
1975	Q G.Ht.	4,520 18.52	62 9.56	177 3.52		635 8.49		455 7.30		
1976	Q G.Ht.	1,380 9.59	45 7.75	365 4.44		73 3.05		135 4.18		
1977	Q G.Ht.	6,200 21.55	28 7.61	107 3.17		1,200 10.17		921 10.34		

heights (G. Ht.), in feet, for Washita River and tributary watersheds

Washita 500	West Bitter 511	East Bitter 512	East Bitter 513	Little Washita 522	Washita 600	Dry 611	Dry 612	Winter 621	Washita 700
						466 2.22	48 1.81		9,670 16.10
	1,180 9.64			1,570 11.74		670 2.54	66 2.14	3,890 10.49	3,980 10.61
4,500 18.79	633 6.96	1,790 8.75		7,560 20.65	4,360 20.88	2,410 8.07	158 2.63	4,460 8.62	5,510 12.64
6,250 22.13	3,120 16.41	3,050 10.73	2,100 9.15	2,610 15.86	5,940 23.18	135 3.34	31 1.71	1,480 6.36	5,800 13.99
2,010 13.55	2,880 15.69	1,630 8.42	1,220 7.58	811 11.77	3,380 19.10	357 4.46	86 2.20	170 3.53	3,350 10.74
7,100 22.78	3,300 16.21	2,490 9.99	1,860 8.77	1,710 13.77	7,820 24.54	100 3.08	167 2.67	1,330 5.91	7,450 15.51
3,410 15.81	382 5.26	533 5.95	257 4.70	5,280 19.14	3,470 18.84	489 4.90	280 3.29	1,610 6.21	3,520 10.89
6,800 22.22	2,760 15.32	2,150 9.35	1,710 8.60	5,050 19.39	10,060 26.71	1,600 7.27	184 2.75	2,030 6.62	9,350 17.83
6,100 20.54	2,840 14.95	1,230 7.82	843 6.75	1,460 13.55	5,450 21.52	706 5.53	230 3.00	2,420 6.81	5,620 13.15
3,150 15.32	3,070 16.51	2,560 10.15	1,380 7.97	3,900 20.44		176 3.60	93 2.25	804 5.20	8,100 16.77
1,160 10.31	1,330 11.31	825 6.82	536 5.82	3,040 18.35		1,590 7.27	324 3.53	2,170 6.63	4,660 13.85
5,090 19.10	2,920 16.05	4,620 12.57	3,490 11.05	5,950 23.81		631 5.33	253 3.14	4,280 7.88	8,850 18.32
3,360 15.29	1,960 12.88	1,310 8.00	1,120 7.43	1,600 14.32		365 4.48	173 2.70	905 5.35	4,790 12.52
5,160 20.50	1,980 11.70	2,660 10.28	1,600 8.39	4,420 22.23				4,020 7.75	8,090 17.10
1,660 11.49	157 3.78	259 4.79	72 3.33	2,110 13.22				1,320 5.90	2,050 8.59
5,800 21.31	1,380 9.49	1,700 8.77	1,490 8.20	2,920 15.57				595 4.84	6,240 14.50

reached Verden disappeared between Verden and Chickasha (26 river-miles). Below Chickasha the flow was contained within banks. The reduction between Chickasha and Alex (30 river-miles) was about 3.5 percent, or less than one-third the rate between Anadarko and Chickasha (Hartman et al. 1969).

Tests were conducted on the Washita River, East Bitter Creek, and Winter Creek to determine the flow loss of water released from impoundments for irrigation. The results were reported by Schoof and DeCoursey (1966), and Schoof and Price (1980).

FLOW CHARACTERISTICS

Water yield.—Water-yield records were collected at 6 Washita River gaging stations and 13 major tributary stations to determine the effect of the flood-abatement program on downstream water yield. Water yield included both storm flow and base flow that passed the gaging stations as surface flow. Underground flow past the gaging stations was thought to be small and insignificant compared to the surface flow.

The annual Theissen-weighted precipitation and water yield for the period of record at each watershed is shown in table 8-2. The average annual precipitation and runoff for the study reach from 1962 to 1977 inclusive were 27.64 and 1.30 inches, respectively. Thus, the runoff was only 4.72 percent of the precipitation. Although precipitation in the reach between stations 500 and 700 (fig. 2-1) was only about 2.5 inches greater than in the reach between stations 100 and 200, the runoff was nearly 3 times greater. Lake Chickasha and small channels through the Tonkawa and Sugar Creek alluvium greatly reduced runoff from the reach between stations 100 and 200.

The average annual tributary runoff expressed as a percentage of the average annual precipitation varied from 1.38 at Tonkawa Creek station 110 to 10.96 at East Bitter Creek station 513. The low percentages of runoff at Tonkawa Creek station 110 and Line Creek station 411 were caused by leakage into the alluvium of the Washita River terraces. Both Tonkawa and Line Creeks had channels generally less than 5 feet deep through the Washita terrace formations. However, a portion of the Tonkawa Creek channel was dredged in 1972. Since then the water yield reaching the Washita River has increased fourfold.

Rush Springs sandstone is highly permeable. Therefore, the watersheds with large outcrop areas of Rush Springs sandstone, including Sugar, Tonkawa, and Delaware Creeks and the Little Washita River, tend to have less storm runoff than watersheds in the Chickasha formation, including Salt, Bitter, and Winter Creeks. However, the natural physical characteristic that has the greatest influence on the magnitude of runoff from watersheds in this area is the extent of alluvium within the watershed.

Flood frequency.—Watershed characteristics that influence the magnitude of peak flow include shape, slope, drainage density, vegetal cover, land use, storage, soil type, and geology. Floods may be measured by height, area inundated, peak discharge, and volume of flow. The annual peak discharge and gage heights at each major tributary and main stem gaging station are shown in table 8-3. The peak discharges for the main stem stations have a high degree of accuracy because the flow was nearly always measured with a current meter at or near the peak. However, many of the maximum peak discharges at the tributary stations were not measured because of inaccessibility, log jams, or not knowing of the event until later. Peak discharges in those events were estimated indirectly.

The highest discharge at a main stem gaging station during the period of record was 11,000 cubic feet per second at Anadarko in 1965. That was the only overbank flow experienced there during the 16-year period of record (1962-77). The highest peak flow at a tributary station was 8,500 cubic feet per second on Sugar Creek in 1965.

Floodwater-retarding structures were installed on many of the tributary watersheds during the period of record. Therefore, neither of the records collected, before or after treatment, was long enough for a flood-frequency analysis. However, the treatment was not applied on Delaware (131), Salt (311), and East Bitter (513) watersheds (fig. 2-1), but 12 years of discharge records were obtained at Winter Creek station 621 for the post-treatment condition. Log Pearson type III peak-flow frequency curves (U.S. Water Resources Council 1967) are shown in figures 8-8 — 8-13 for those four tributary stations and Washita River stations at Anadarko (100) and Alex (700). The computed skew coefficients for the six stations were as follows: station 100, -0.11; station 131, -0.50; station 311, 0.09; station 513, -1.63; station 621, -0.006; and station 700, -0.77. Ac-

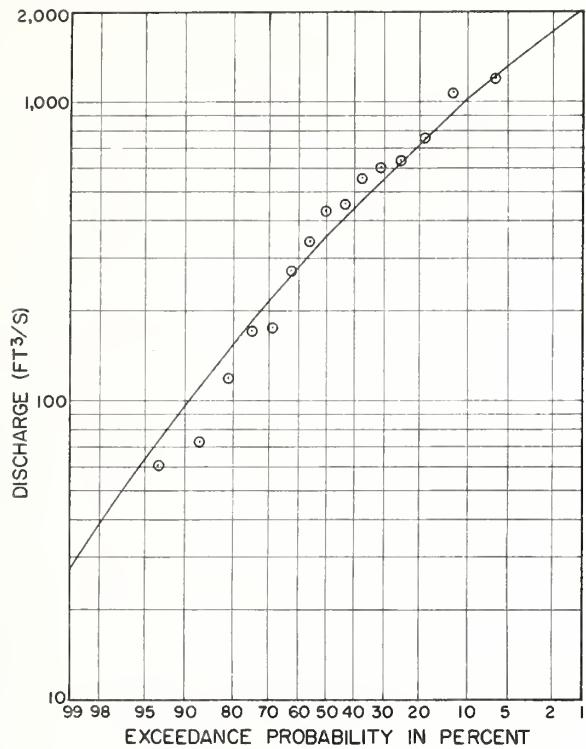


FIGURE 8-8.—Flood-frequency curve for Delaware Creek station 131.

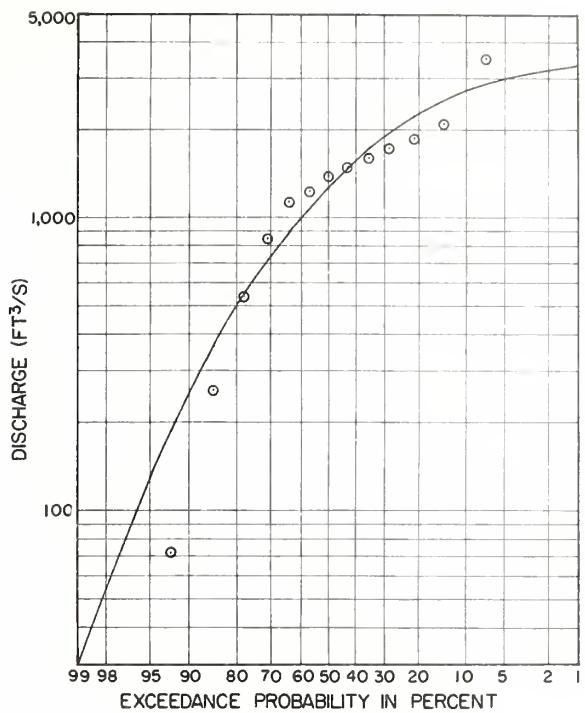


FIGURE 8-10.—Flood-frequency curve for East Bitter Creek station 513.

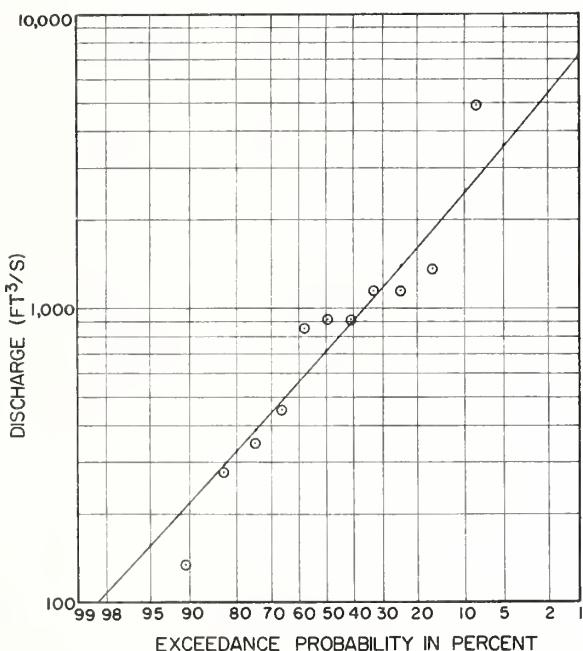


FIGURE 8-9.—Flood-frequency curve for Salt Creek station 311.

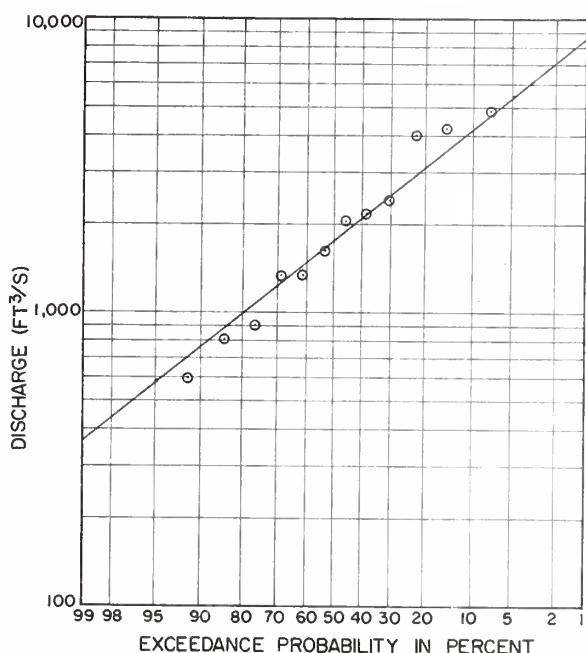


FIGURE 8-11.—Flood-frequency curve for Winter Creek station 621.

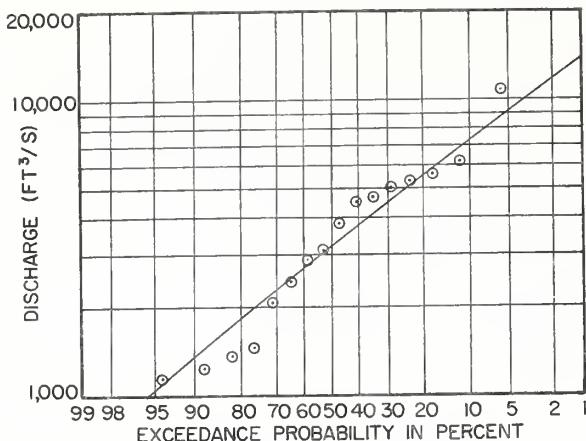


FIGURE 8-12.—Flood-frequency curve for Washita River station 100 at Anadarko.

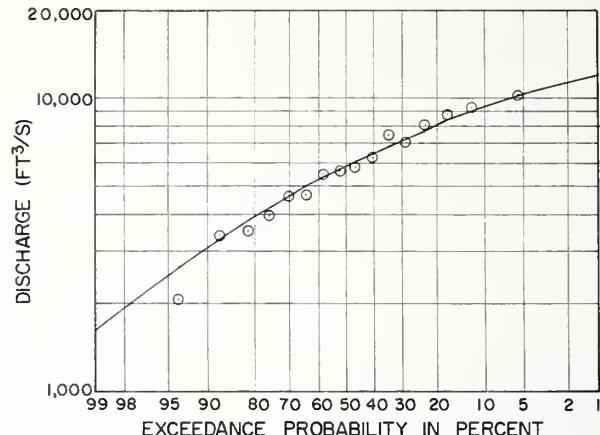


FIGURE 8-13.—Flood-frequency curve for Washita River station 700 at Alex.

curacy of the curves is probably poor for the low-frequency events because the period of record was short for flood-frequency analysis, and no adjustment was made to longer records at other stations. The indicated frequencies are probably low because average annual rainfall during the period of record was less than the long-term average.

Flow duration.—Flow-duration curves have been used since about 1915 for determining the effect of geology on low flows; for water-power studies, including plant capacity; for determining the economic feasibility of projects; for determining storage requirements in stream pollution; for water-quality studies; and for irrigation water-supply studies. The flow-duration curve is used to analyze the availability and variability of streamflow. The shape of flow-duration curves may indicate ground-water contribution to the stream, geologic structure, topography, soil characteristics, type of vegetation, etc., and is a means of relating the characteristics of streams.

A flow-duration curve is developed by arraying the recorded daily discharges at a gaging station in order of magnitude, computing the percentage of time the various rates of discharge are equalled or exceeded, and then plotting the discharge rates against the corresponding percentages of time. The resulting curve defines the frequency of various rates of flow without regard to chronological sequence (Searcy 1959).

Flow-duration curves for the Washita River at Anadarko and Alex and for selected tributaries are shown in figures 8-14–8-19. The curves for the Washita River stations were developed from

daily flows. However, the curves for the tributary watersheds were developed from detailed discharge data ranging in time increments from 0.1 to 24 hours. Also shown in figures 8-14–8-19 are flow-yield distribution curves showing the percentage of total flow yield that flowed at rates equal to or exceeding the rates plotted on the ordinate. The curves show the relative importance of the contribution of the various flow rates to the total flow. If this information is available when a flume or weir is designed for a gaging station, it would indicate which flow rates have the greatest sensitivity of measurement.

Comparison of the flow-duration curves for the Washita River at Anadarko and Alex (figs. 8-18 and 8-19) show that they cross at about 20 cubic feet per second. Thus, the flow was less than that for a greater percentage of time at Alex than at Anadarko. This was probably caused by irrigation withdrawal near Chickasha. At stations 131 and 513 the flow-duration-curve slopes (figs. 8-14 and 8-16) are least in the log cycle from 1 to 10 cubic feet per second, indicating that the flow was in that range a relatively large percentage of time. Station 513 had the least time with no flow because it received the greatest rainfall. The flow at station 513 exceeded 0.05 cubic foot per second about 90 percent of the time, whereas the flow at station 311 exceeded that rate only 67 percent of the time. The drainage areas of these two watersheds are nearly the same.

Figure 8-15 shows that 50 percent of the total volume of flow at station 311 was at rates ex-

(Continued on page 93.)

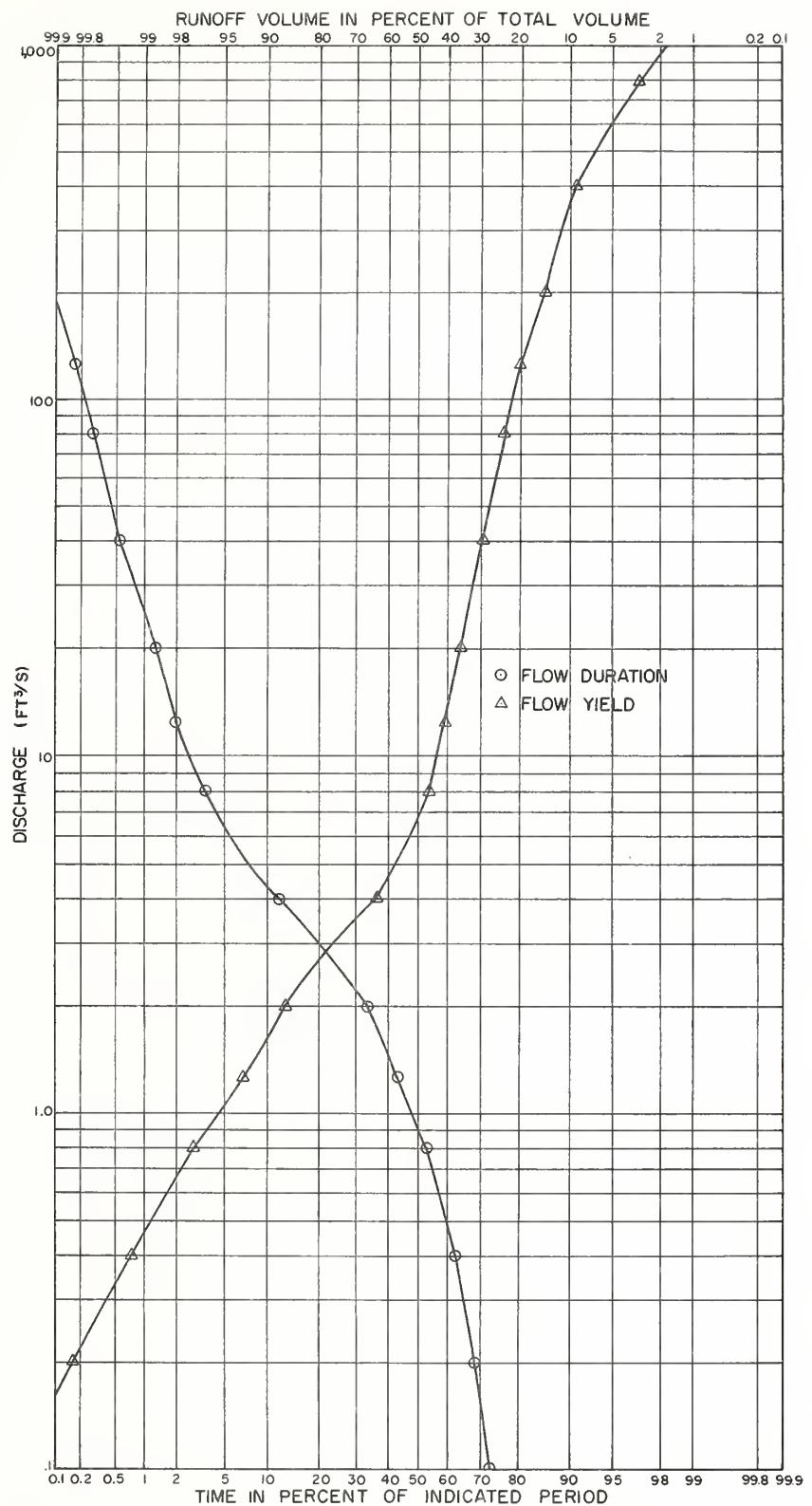


FIGURE 8-14.—Flow-duration and flow-yield curves for Delaware Creek station 131, 1963-77.

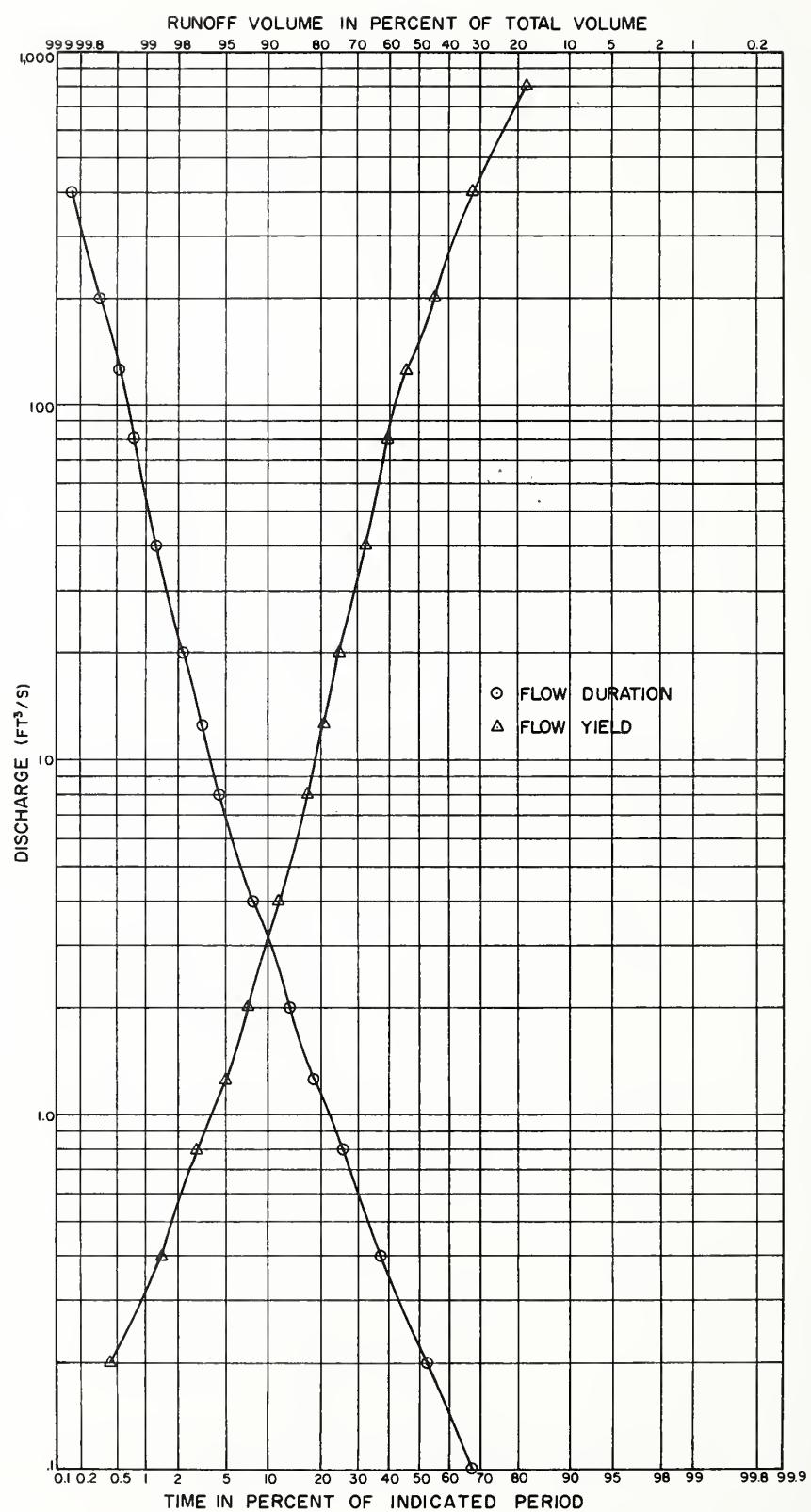


FIGURE 8-15.—Flow-duration and flow-yield curves for Salt Creek station 311, 1967-77.

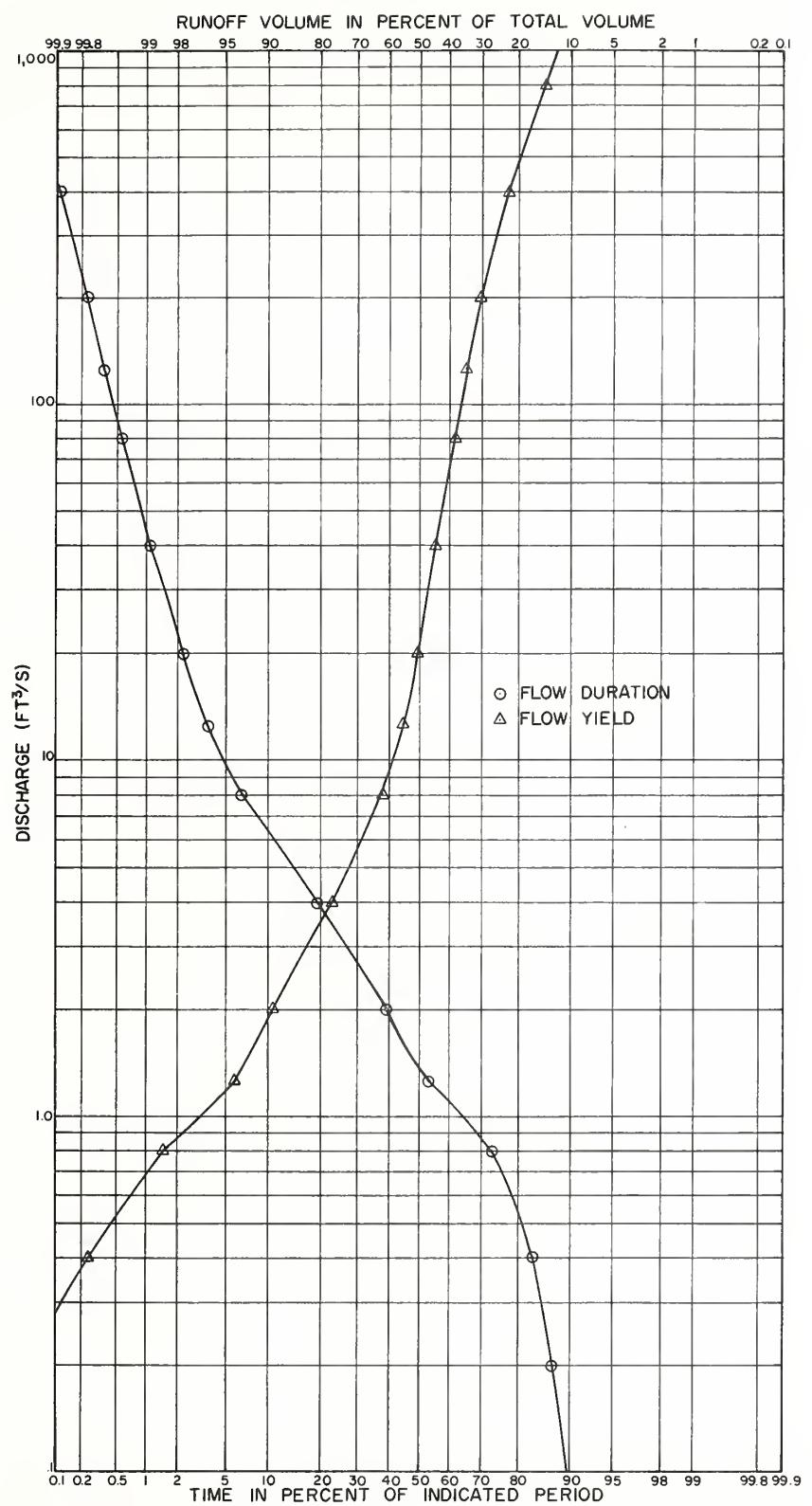


FIGURE 8-16.—Flow-duration and flow-yield curves for East Bitter Creek station 513, 1965-77.

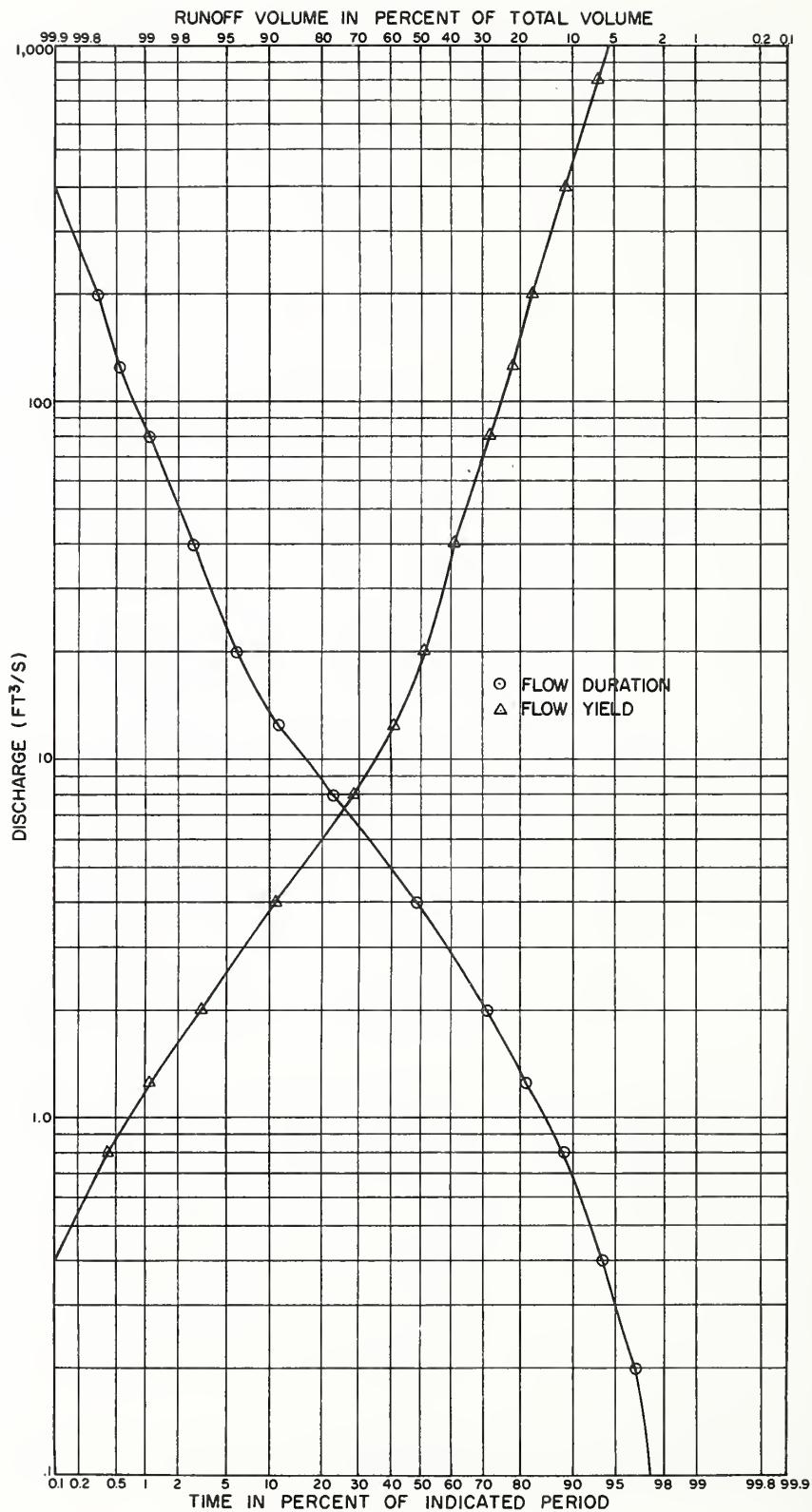


FIGURE 8-17.—Flow-duration and flow-yield curves for Winter Creek station 621, 1967-77.

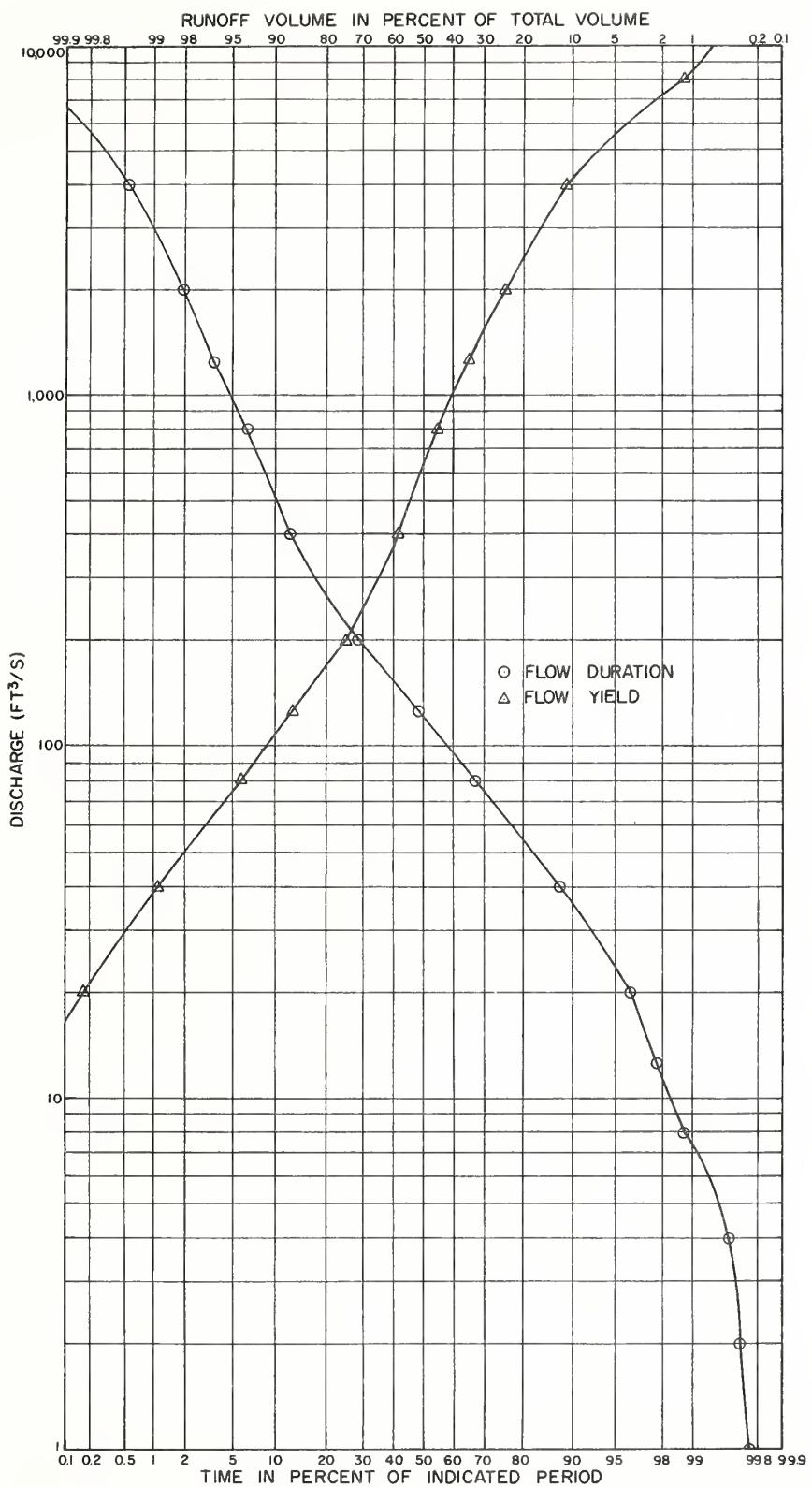


FIGURE 8-18.—Flow-duration and flow-yield curves for Washita River station 100 at Anadarko, 1962-77.

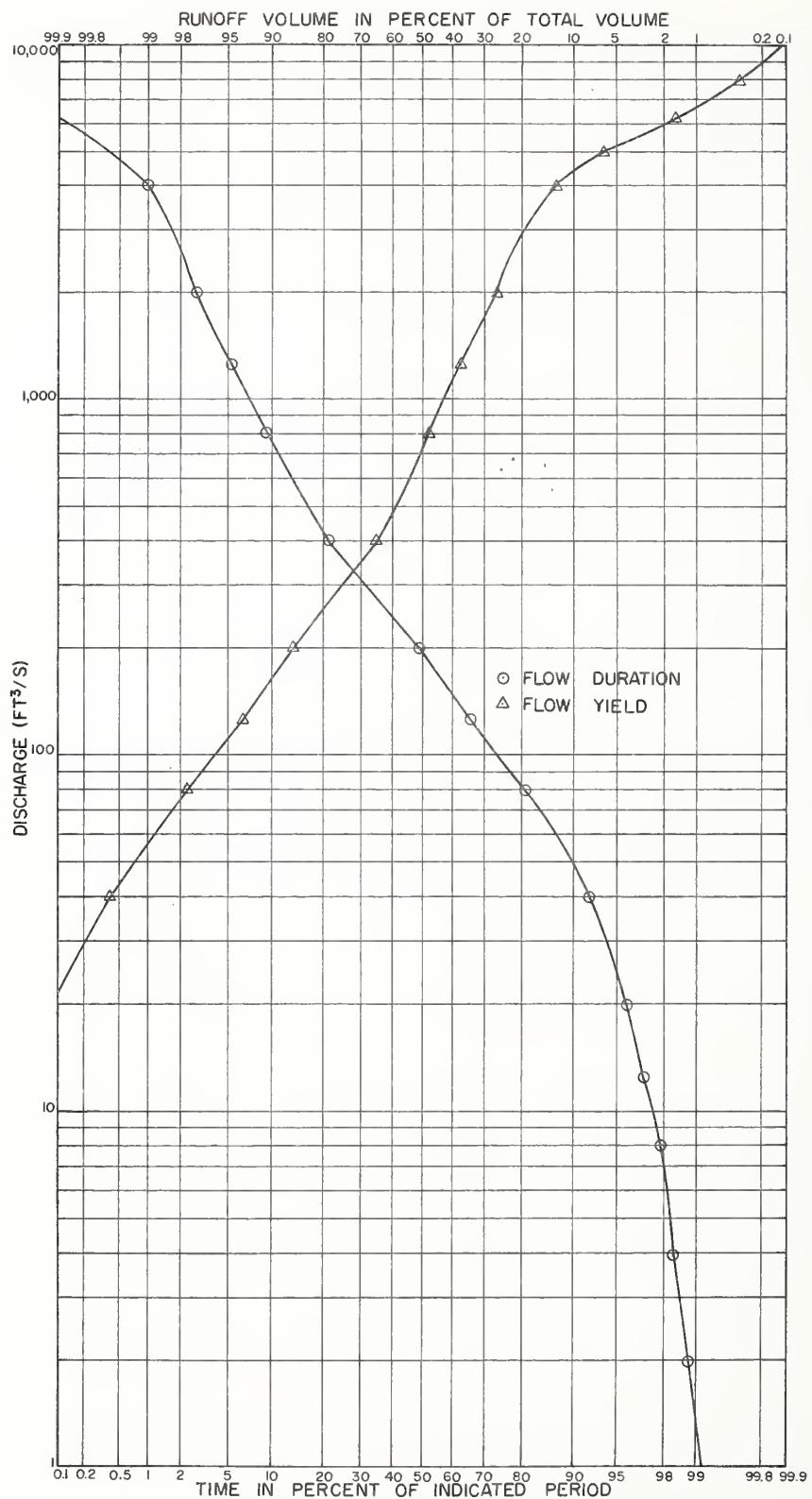


FIGURE 8-19.—Flow-duration and flow-yield curves for Washita River station 700 at Alex, 1962-77.

ceeding 150 cubic feet per second. However, the 50-percent lines for stations 131 and 513 fall at 7 and 20 cubic feet per second, respectively. The flood peak of 4,900 cubic feet per second at station 311 in 1967 was probably overestimated. However, we had no good basis for making a correction of that event.

The 2 years of record preceding the treatment of Winter Creek (621) are insufficient to define the pretreatment condition. However, flow-duration and flow-yield curves are shown in figure 8-17 for the posttreatment condition. The flow rate exceeded 0.05 cubic foot per second for 97 percent of the time. The base flow cannot be separated from low-flow drainout from impoundment storage. However, flows at rates less than 1 cubic foot per second were probably dry-weather base flows.

Minimum flow.—The flow of a stream during periods of drought is important to all streamflow users who must have a dependable water supply. Analysis of the low-flow characteristics of a stream is necessary to determine the storage requirements in meeting the need for water during periods of little or no flow. Rainfall (table 8-2), timber removal (table 2-6), and installation of floodwater-retarding structures (table 2-9), had some effects on the low flow of the study-reach streams during the period of record. However, isolating the effect of each of these variables is not always possible.

Annual minimum volume of flow in cubic feet per second-days for selected time intervals of 1 to 90 days at the Washita River and major tributary gaging stations is shown in table 8-4. (A second-foot-day is the volume represented by 1 cubic foot per second flowing for 24 hours.) The river station records include water released from Fort Cobb Reservoir for irrigation or municipal use in 1964, 1967, 1970, and 1972. During those releases, there was generally more low flow at Verden (200) than at Chickasha (500) because of discharge from the Anadarko sewage disposal system (Schoof and DeCoursey 1966). The most extended period of drought during the period of record was in 1972 when several of the tributaries had no flow for more than 90 days. Oxbow lakes between stations 111 and 110 on Tonkawa Creek absorbed much of the flow. However, the stream was perennial at station 110 in 1975 because there was abundant rainfall. Dredging of the Sugar Creek channel in 1967 and Tonkawa Creek channel in 1973-74 caused an increase in the low flow of both streams.

SUMMARY

Determining the effect of the SCS floodwater-retarding structures on the downstream water yield of large watersheds is extremely difficult because the effects of climatic variation, timber removal, farm-pond construction, U.S. Bureau of Reclamation reservoirs, and land-use changes are intermingled. Some fault can be found with any conclusion that one makes concerning causative effects of changes in the water yield from large watersheds. There is no conclusive proof that floodwater-retarding structures on the Washita River watershed have either decreased or increased water yield from the entire watershed.

There was an indication of a reduction in the water yield of Tonkawa and Rush Creeks attributable to the structures. However, a double-mass runoff comparison of untreated Delaware Creek with the 1,130-square-mile Washita study reach showed no change in the water yield of the study reach, with structures controlling runoff from up to 34 percent of the drainage area. Apparently, the dredging of Tonkawa and Sugar Creeks, combined with considerable removal of timber, increased the water yield from the study reach as much as all of the structures decreased it.

On Sugar and Winter Creeks, the floodwater-retarding structures reduce peak flows by a percentage equal to the percentage of the drainage area that is controlled by the structures. However, this may not be true of all watersheds. A flood-frequency study on Winter Creek indicated that a peak discharge that occurred on the average every 2 years before treatment would occur on the average every 5 years following treatment. Similarly, a pretreatment peak discharge that occurred on the average every 10 years would occur on the average about every 100 years after treatment.

A study of flow loss from runoff events on the Washita River in the reach from Anadarko to Verden revealed that there was a subsequent recovery of flow abstraction from runoff events in the dormant season through increased base flow. However, flood abstractions were not recovered for runoff events during the growing season. The average annual precipitation and runoff for the study reach from 1962 to 1977 inclusive were 27.64 and 1.30 inches, respectively. Thus, the runoff was only 4.72 percent of the precipitation.

(Continued on page 100.)

Table 8-4.—Annual minimum volume of flow, in cubic feet per second-days, for selected time intervals

Year	1 Day	4 Days	7 Days	14 Days	30 Days	60 Days	90 Days
Washita River at Anadarko (100)							
1962	76.0	304.0	532.0	1139.0	3350.0	9925.0	15661.0
1963	24.0	99.0	183.0	397.0	978.0	2725.0	4494.0
1964	0.0	1.1	2.5	6.4	301.1	2293.1	7810.0
1965	21.0	99.0	196.0	417.0	1210.0	3376.0	13661.0
1966	16.0	68.0	129.0	366.0	956.0	3052.0	5364.0
1967	1.6	11.0	25.4	94.4	610.4	2088.4	4460.0
1968	45.2	190.7	346.1	708.0	1799.4	4198.6	6598.0
1969	55.0	225.0	428.0	885.0	2306.0	5353.0	9362.0
1970	2.7	15.9	31.2	85.5	463.7	1347.8	3238.9
1971	4.1	18.9	36.9	102.9	269.6	761.6	2211.6
1972	0.3	3.1	14.0	97.1	494.2	2100.5	2804.7
1973	39.3	162.2	286.1	665.7	2035.4	8023.6	15634.2
1974	11.0	47.0	91.0	218.0	666.0	3791.0	10765.0
1975	146.0	606.0	1083.0	2255.0	5518.0	12334.0	19420.0
1976	25.0	102.0	191.0	451.0	1266.0	3366.0	7831.0
1977	57.0	237.0	431.0	911.0	2246.0	5043.0	8203.0
Tonkawa Creek East of Anadarko (110)							
1964	.0	.0	.0	.0	.0	.0	.0
1965	.0	.0	.0	.0	.0	.0	.0
1966	.0	.0	.0	.0	.0	.0	.0
1967	.0	.0	.0	.0	.0	.0	.0
1968	.0	.0	.0	.0	.0	.0	.0
1969	.0	.0	.0	.0	.0	.0	.0
1970	.0	.0	.0	.0	.0	.0	.0
1971	.0	.0	.0	.0	.0	.0	.0
1972	.0	.0	.0	.0	.0	.0	.0
1973	.0	.0	.0	.0	.0	.0	.0
1974	.0	.0	.0	.0	.0	.0	.0
1975	.1	.7	1.8	5.1	18.1	51.1	103.0
1976	.0	.0	.0	.0	.0	.0	.0
1977	.0	.0	.0	.0	.0	.0	.0
Tonkawa Creek South of Anadarko (111)							
1963	.0	.0	.0	.0	.0	1.1	3.8
1964	.0	.0	.0	.0	.0	4.6	16.1
1965	.0	.0	.0	.0	1.2	8.2	18.3
1966	.0	.0	.0	.0	.0	7.1	20.5
1967	.0	.0	.0	.0	.0	3.7	13.1
1968	.0	.0	.0	.0	.9	20.7	51.5
1969	.0	.0	.0	.0	.0	5.0	12.3
1970	.0	.0	.0	.0	.0	.0	.6
1971	.0	.0	.0	.0	.0	1.5	12.7
1972	.0	.0	.0	.0	.0	.0	.0
1973	.0	.0	.0	.6	4.8	29.1	78.3
1974	.0	.0	.0	.0	.1	8.3	22.9
1975	.7	3.3	5.9	13.4	39.3	80.3	139.2
1976	.0	.0	.0	.0	.7	9.0	20.8
1977	.0	.0	.0	.0	.0	.6	1.0

Table 8-4.—Annual minimum volume of flow, in cubic feet per second-days, for selected time intervals—Continued

Year	1 Day	4 Days	7 Days	14 Days	30 Days	60 Days	90 Days
Sugar Creek near Gracemont (121)							
1962	.0	.0	.0	.0	2.8	108.7	731.5
1963	.0	.0	.0	.0	.0	56.3	191.1
1964	.0	.0	.0	.0	.0	.0	3.6
1965	.0	.0	.0	.0	.0	2.4	487.6
1966	.0	.0	.0	.0	2.0	32.7	130.5
1967	.1	.4	.7	1.6	4.0	21.0	102.2
1968	.2	1.0	2.2	9.1	148.5	616.8	1126.4
1969	.0	4.6	8.5	25.3	70.4	205.7	487.3
1970	.0	.1	.3	1.2	3.5	9.9	48.8
1971	.0	.0	.0	.0	4.8	60.3	113.5
1972	.0	.0	.0	.0	.2	1.4	5.5
1973	.0	.5	1.7	7.3	24.4	308.6	687.2
1974	.1	.4	.7	1.5	5.5	226.1	596.9
Delaware Creek near Anadarko (131)							
1963	.0	.0	.0	.0	.0	.0	.0
1964	.0	.0	.0	.0	.0	.1	7.5
1965	.0	.0	.0	.0	.0	2.1	5.9
1966	.0	.0	.0	.0	.0	.0	.6
1967	.0	.0	.0	.0	.0	.5	3.7
1968	.0	.0	.0	.0	.0	10.0	25.1
1969	.0	.0	.0	.0	.0	1.9	5.1
1970	.0	.0	.0	.0	.0	.0	.4
1971	.0	.0	.0	.0	.0	6.7	19.3
1972	.0	.0	.0	.0	.0	.0	.0
1973	.1	.4	.7	2.2	16.5	109.0	251.0
1974	.0	.0	.0	.0	.0	12.3	24.1
1975	.6	2.4	4.3	11.0	37.0	77.6	133.0
1976	.0	.0	.0	.0	.3	9.7	25.1
1977	.0	.0	.0	.1	.4	5.4	18.4
Washita River at Verden (200)							
1962	79.0	316.0	561.0	1256.0	3920.0	11180.0	17880.0
1963	19.0	92.0	169.0	378.0	953.0	2749.0	4822.0
1964	1.3	9.0	18.9	42.3	336.7	2529.6	8924.2
1965	24.0	100.0	189.0	426.0	1232.0	3540.0	14938.0
1966	19.0	81.0	144.0	463.0	1069.0	3352.0	6564.0
1967	5.3	25.8	47.3	130.0	732.0	2358.0	5197.0
1968	56.0	229.0	403.0	809.0	2158.0	5202.0	8248.0
1969	63.0	260.0	491.0	1001.0	2744.0	6229.0	9726.0
1970	2.2	12.2	33.5	91.0	445.5	1351.4	3409.9
1971	2.2	14.1	38.1	98.6	258.4	759.7	2428.7
1972	1.3	12.5	27.4	100.3	455.4	1902.6	2494.3
1973	38.0	165.0	304.0	720.0	2353.0	9021.0	18045.0
1974	11.0	46.0	89.0	232.0	736.0	4726.0	12161.0

Table 8-4.—Annual minimum volume of flow, in cubic feet per second-days, for selected time intervals—Continued

Year	1 Day	4 Days	7 Days	14 Days	30 Days	60 Days	90 Days
Salt Creek near Pocasset (311)							
1967	.0	.0	.0	.0	.0	.5	2.1
1968	.0	.0	.0	.0	.0	4.9	6.9
1969	.0	.0	.0	.0	.0	.2	8.9
1970	.0	.0	.0	.0	.0	3.5	9.5
1971	.0	.0	.0	.0	1.8	6.0	13.3
1972	.0	.0	.0	.0	.0	.0	.0
1973	.0	.0	.0	.0	1.7	12.2	78.3
1974	.0	.0	.0	.0	.6	3.0	106.9
1975	.4	2.1	4.1	8.9	21.6	52.7	88.4
1976	.0	.0	.0	.0	.0	2.0	5.6
1977	.0	.0	.0	.0	.0	.0	.9
Line Creek at Chickasha (411)							
1963	.0	.0	.0	.0	.0	.0	.0
1964	.0	.0	.0	.0	.0	.3	.5
1965	.0	.0	.0	.0	.0	.0	1.0
1966	.0	.0	.0	.0	.0	.5	.8
1967	.0	.0	.0	.0	.0	.0	.7
1968	.0	.0	.0	.0	.0	1.0	3.7
1969	.0	.0	.0	.0	.0	.9	3.2
1970	.0	.0	.0	.0	.0	.6	4.2
1971	.0	.0	.0	.0	.0	.5	4.4
1972	.0	.0	.0	.0	.0	.5	1.1
1973	.0	.0	.0	.0	1.1	27.0	95.8
1974*	.1	.7	1.3	3.1	9.4	29.9	60.5
Washita River at Bailey Turnpike (500)							
1964	.0	.0	.2	1.2	167.7	2254.6	8662.6
1965	23.0	104.0	191.0	429.0	1699.0	5162.0	15374.0
1966	9.2	50.2	100.2	359.0	921.2	3233.2	6281.0
1967	.1	.6	3.9	61.1	517.1	2175.1	5822.0
1968	58.0	240.7	424.5	859.4	2279.3	5384.3	8489.4
1969	48.0	221.0	418.0	893.0	2469.0	5879.0	9796.0
1970	.2	1.3	11.5	53.7	278.9	1153.5	3895.9
1971	.5	4.2	14.6	52.2	221.0	784.8	2562.8
1972	.7	5.1	9.7	38.2	278.1	1477.1	1854.1
1973	37.0	172.0	318.0	770.0	2551.0	9197.0	18794.0
1974	5.6	38.1	91.1	284.1	1070.1	5554.1	16313.1
1975	185.0	754.0	1335.0	2743.0	6777.0	15204.0	23297.0
1976	29.0	128.0	244.0	554.0	1633.0	4435.0	9126.0
1977	70.0	297.0	542.0	1176.0	2733.0	6258.0	10068.0

* Partial Year--Record discontinued September 30, 1974.

Table 8-4.—Annual minimum volume of flow, in cubic feet per second-days, for selected time intervals—Continued

Year	1 Day	4 Days	7 Days	14 Days	30 Days	60 Days	90 Days
West Bitter Creek near Tabler (511)							
1963	.0	.0	.2	.9	2.9	8.1	15.1
1964	.0	.0	.0	.0	.0	20.2	110.2
1965	.0	.0	.0	.0	15.4	38.5	80.5
1966	.0	.0	.0	.0	.0	9.4	24.1
1967	.0	.0	.0	.0	.7	3.7	53.6
1968	.0	.0	.0	.0	9.0	80.0	191.1
1969	.0	.0	.0	.1	20.5	98.2	164.1
1970	.0	.0	.0	.0	.0	8.0	35.3
1971	.0	.0	.0	.0	.0	23.0	74.9
1972	.0	.0	.0	.0	.0	.0	.0
1973	1.0	4.0	7.0	32.6	162.3	453.8	1195.9
1974	.7	3.3	6.6	13.8	40.0	204.4	609.2
1975	4.9	21.1	39.1	84.3	189.3	400.0	605.0
1976	.4	1.6	2.8	5.6	17.4	84.3	129.1
1977	.0	.0	.0	.6	3.6	12.1	19.2
East Bitter Creek at Tabler (512)							
1964	.0	.0	.0	.0	.0	36.3	176.3
1965	.0	.0	.0	1.8	9.4	78.6	156.8
1966	.0	.0	.0	.3	2.0	58.4	126.5
1967	.0	.0	.0	.0	.7	14.3	66.8
1968	.1	.4	.7	1.6	9.4	80.8	175.3
1969	.2	1.0	2.6	6.2	36.7	124.8	210.4
1970	.0	.0	.0	.0	.0	4.4	22.3
1971	.0	.0	.0	.0	3.6	58.5	109.6
1972	.0	.0	.0	.0	.0	1.4	1.4
1973	2.0	8.1	14.4	55.8	189.7	523.2	1070.0
1974	.7	3.2	6.2	16.0	40.4	142.7	391.6
1975	4.3	17.4	31.2	64.9	151.9	315.8	482.0
1976	.4	1.8	4.2	9.4	21.8	73.2	113.1
1977	.1	.6	1.4	3.2	10.8	24.8	39.8
East Bitter Creek near Tabler (513)							
1965	.0	.0	.0	.0	2.9	34.9	83.6
1966	.0	.0	.0	.0	.0	19.8	62.5
1967	.0	.0	.0	.0	.6	8.6	41.3
1968	.0	.0	.0	.0	3.3	23.6	72.8
1969	.0	.3	.8	2.5	18.6	61.5	103.0
1970	.0	.0	.0	.0	.0	.6	14.5
1971	.0	.0	.0	.0	.0	27.7	48.5
1972	.0	.0	.0	.0	.0	1.1	1.1
1973	1.5	6.0	10.8	25.2	86.1	292.6	597.8
1974	.4	1.6	2.9	6.5	17.1	77.7	245.7
1975	2.7	11.1	19.5	40.4	88.9	189.9	289.4
1976	.1	.4	1.1	2.4	6.4	30.7	50.2
1977	.0	.0	.0	.3	1.8	5.7	9.4

Table 8-4.—Annual minimum volume of flow, in cubic feet per second-days, for selected time intervals—Continued

Year	1 Day	4 Days	7 Days	14 Days	30 Days	60 Days	90 Days
Little Washita River near Ninnekah (522)							
1962	4.0	17.4	31.6	68.4	196.4	891.4	1868.0
1963	.0	.0	.0	.9	15.5	62.2	116.4
1964	.0	.0	.0	.0	12.1	88.0	263.7
1965	.1	.4	.7	12.4	49.7	229.5	729.9
1966	.0	.0	.0	.0	14.8	78.0	282.6
1967	.0	.0	.0	.0	5.9	128.8	270.4
1968	.1	.4	.8	3.6	39.1	417.8	922.2
1969	.4	3.9	11.4	30.7	85.9	289.7	585.3
1970	.0	.0	.0	.0	.0	4.6	37.0
1971	.0	.0	.0	.0	12.7	162.2	475.1
1972	.0	.0	.0	.0	.0	9.6	18.7
1973	8.8	37.6	74.6	228.0	662.0	1478.6	3720.6
1974	4.0	16.3	29.8	65.4	198.3	905.2	1351.1
1975	17.0	74.0	134.0	285.0	713.0	1484.0	2457.0
1976	.3	5.5	17.1	52.3	232.0	686.1	1019.0
1977	3.8	15.9	28.5	62.6	165.1	472.8	850.3
Washita River near Tabler (600)							
1964	.0	.0	1.2	4.1	222.5	3124.5	9917.0
1965	23.0	99.0	194.0	435.0	1892.0	8921.0	18444.0
1966	11.0	60.0	116.0	307.0	1194.0	3624.0	7431.0
1967	.0	.0	.6	15.9	445.1	2447.1	6497.1
1968	62.0	259.0	489.0	1021.0	2868.0	6653.0	10926.0
1969	49.0	217.0	395.0	922.0	2568.0	6503.0	11154.0
1970	.1	1.1	2.3	7.9	77.5	986.4	3562.4
Dry Creek near Alex (611)							
1962	0.0	0.1	0.4	1.6	4.9	31.1	42.9
1963	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1964	0.0	0.0	0.0	0.0	0.0	0.4	0.7
1965	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1966	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1967	0.0	0.0	0.0	0.0	0.0	0.0	0.2
1968	0.0	0.0	0.0	0.0	1.1	8.7	14.7
1969	0.0	0.0	0.0	0.0	0.1	0.8	6.9
1970	0.0	0.0	0.0	0.0	0.0	0.1	3.5
1971	0.0	0.0	0.0	0.0	0.0	4.8	22.8
1972	0.0	0.0	0.0	0.5	2.2	5.0	8.1
1973	0.5	2.0	3.7	8.4	27.4	78.2	163.8
1974	0.1	0.4	0.7	1.4	4.0	23.2	35.9

Table 8-4.—Annual minimum volume of flow, in cubic feet per second-days, for selected time intervals—Continued

Year	1 Day	4 Days	7 Days	14 Days	30 Days	60 Days	90 Days
Dry Creek near Alex (612)							
1962	0.1	0.4	0.7	1.4	3.0	6.3	11.3
1963	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1964	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1965	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1966	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1967	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1968	0.0	0.0	0.0	0.0	0.0	0.0	0.5
1969	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1970	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1971	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1972	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1973	0.0	0.0	0.0	0.0	0.0	0.5	2.4
1974	0.0	0.0	0.0	0.0	0.0	0.1	2.3
Winter Creek near Alex (621)							
1963	0.0	0.0	0.0	0.3	1.3	9.2	26.8
1964	0.0	0.0	0.0	0.0	0.0	35.8	152.8
1965	0.0	0.0	0.0	0.5	12.0	63.8	226.8
1966	0.0	0.0	0.0	0.0	3.9	60.2	124.3
1967	0.0	0.0	0.0	0.0	2.0	25.7	69.2
1968	0.1	0.6	1.3	3.7	20.0	71.0	177.5
1969	0.5	2.2	4.4	12.4	69.7	182.0	297.9
1970	0.0	0.0	0.0	0.0	0.0	3.1	20.1
1971	0.0	0.3	1.0	4.4	22.0	107.9	200.4
1972	0.0	0.0	0.1	0.9	4.3	14.7	34.8
1973	2.5	11.1	19.8	44.6	140.9	377.0	697.6
1974	0.6	2.5	4.6	12.3	41.2	147.2	289.3
1975	2.1	9.7	18.4	37.3	104.3	217.5	355.9
1976	0.7	2.8	5.3	11.1	28.0	85.1	146.1
1977	0.2	0.8	1.9	5.2	16.5	41.1	67.6
Washita River near Alex (700)							
1962	79.0	330.0	612.0	1516.0	4527.0	17475.0	27221.0
1963	7.1	35.2	61.6	155.4	607.4	2511.3	6123.9
1964	0.0	0.0	0.0	1.6	173.9	3551.9	10626.8
1965	13.0	86.0	165.0	456.0	1840.0	10478.0	18684.0
1966	9.9	51.9	127.0	307.0	1266.9	3668.9	7700.0
1967	0.1	0.6	3.0	21.6	464.3	2416.3	6339.3
1968	67.0	283.0	505.0	1060.0	3063.0	6903.0	11362.0
1969	53.0	238.0	434.0	986.0	2871.0	7207.0	11293.0
1970	0.0	0.0	0.1	5.8	78.3	994.5	3522.5
1971	1.6	7.9	20.1	111.6	437.6	1254.6	3532.6
1972	0.0	0.1	1.8	8.0	118.4	1120.7	1522.1
1973	62.0	269.0	489.0	1182.0	4356.0	17068.0	32025.0
1974	12.0	56.0	115.0	346.0	1437.0	7314.0	20486.0
1975	228.0	940.0	1689.0	3555.0	8695.0	18815.0	28084.0
1976	25.0	144.0	268.0	593.0	1895.0	6522.0	12021.0
1977	89.0	374.0	678.0	1455.0	3479.0	8018.0	13014.0

The effect of geology on runoff is intermingled with the effect of precipitation because both change from west to east. However, the greatest runoff probably occurs on the Cloud Chief formation, followed by Chickasha, Rush Springs, and alluvium. The extent of alluvium within a watershed has a great influence on the runoff. The alluvium acts as a sponge during runoff events and then releases the water to evapotranspiration.

The highest discharge at a main stem gaging station during the period of record was 11,000 cubic feet per second at Anadarko in 1965. The highest peak flow at a tributary station was 8,500 cubic feet per second on Sugar Creek in 1965. Flood-frequency studies were limited by the short period of record and installation of floodwater-retarding structures. The skew coefficients for flow-frequency curves for selected watersheds were highly variable.

Flow-duration curves for the Washita River at Anadarko and Alex cross at about 20 cubic feet per second, indicating that the flow was less than 20 cubic feet per second for a greater percentage of time at Alex than at Anadarko. This was probably caused by large irrigation withdrawal near Chickasha.

Water was purchased and released from Fort Cobb Reservoir for irrigation or municipal use in 1964, 1967, 1970, and 1972. The most severe drought during the period of record occurred in 1972 when several of the tributaries had no flow for more than 90 days.

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Section 9.—Sediment Yield From Various Sediment-Source Areas

INTRODUCTION

In order to test existing erosion and sediment-yield estimating procedures for watersheds and to develop new procedures, hydrologic data from small sediment-source watersheds are essential. Therefore, sediment yields were measured for 11 years from field-size unit-source watersheds, ranging in size from 1.5 to 44.3 acres, within the 1,130-square-mile research watershed.

MEASURED SEDIMENT YIELDS

The yields from the sediment-source areas studied and the watershed descriptions are shown in table 9-1. The locations of the unit-source watersheds are given in figure 4-1. The highest yielding watersheds, R-7 and R-8, were overgrazed and gullied rangelands that were formerly cultivated. Sediment yield from the ungullied portion of watershed R-7 was measured at watershed R-9. The sediment contribution from the gullied area was estimated by using data from these two watersheds. The gullied area in watershed R-7 comprised only 1.8 percent of the watershed but contributed over 50 percent of the total yield. The gullied area in watershed R-10 comprised 21.6 percent of the watershed and contributed over 90 percent of the total yield. Individual storm data from watershed R-10 indicate that storms producing runoff from only the gullied area contributed very little to the total sediment yield. Runoff from outside the gully was required to transport the material eroded from the gully by direct rainfall and runoff. Therefore, the total area contributing runoff to the gully was one of the major factors in determining the yield

from the gully. Thus, diverting runoff from a gully should reduce erosion and allow healing to begin.

The irrigated cotton watersheds were the highest sediment-yielding row-crop watersheds. Runoff from the irrigated cotton averaged more than an inch greater than that from the dryland cotton. Sediment yields from the irrigated cotton were approximately three times greater than those from the dryland cotton. These differences indicate the importance of soil-moisture levels at the time of a storm event.

Sediment yields from the remaining cropland watersheds averaged less than 1 ton per acre per year. However, the highest annual yield from each of these watersheds exceeded 1 ton per acre. Most of the high annual yields were associated with storm events within a month of seeding time or when the least vegetative cover was present on a watershed.

EROSION AND SEDIMENT-YIELD ESTIMATES

In tables 9-2 and 9-3, the measured sediment yields for the period of record for various watersheds can be compared with erosion estimates by the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) and sediment-yield estimates by the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975). The USLE estimates were made by using an average annual *R* (rainfall and runoff factor) value of 240 from Agriculture Handbook 537. The *C* (cover and management factor) values were varied within and among years, depending on *EI* (energy times intensity) distribution and crop stage on the cropland and on *EI* distribution and type and

(Continued on page 107.)

Table 9-1.—Watershed description and measured sediment yields from sediment-source areas

Sediment-source area	No.	Watershed			Annual sediment yield (tons/acre)				
		Area (acres)	Average slope (pct)	Average slope length (ft)		No. soil series	Average USLE K value ¹	High	Low	Avg.
Dryland cotton	C-1	17.83	0.4	400	2	0.35	1.4	0.0	0.5
Irrigated cotton	{ C-3 C-4	44.26 29.93	.2 .2	810 620	2 2	.36 .37	3.4 4.0	.4	1.6
Continuous wheat	{ C-5 C-6	12.75 13.00	.5 .6	260 290	2 2	.35 .35	1.3 1.8	0	.4
Mixed row crop and alfalfa	C-7	26.52	.3	570	2	.35	4.1	0	.6
4-yr alfalfa-wheat rotation	C-8	27.28	.7	370	2	.36	1.1	0	.7
Virgin rangeland, properly grazed	{ R-5 R-6	23.72 27.22	3.6 5.1	520 590	3 3	.37 .37	.1 .9	0	.2
Formerly cultivated rangeland, overgrazed	{ R-7 R-8 R-8	19.19 27.55 27.55	4.2 4.7 4.7	590 420 420	3 4 4	.33 .34 .34	29.6 14.2 13.6	.3 1.1 21.0	.2 3.9
Formerly cultivated rangeland, gullied ²	R-9	9.30	4.4	630	3	.33	9.7	.3	2.5
Formerly cultivated rangeland, gullied ²	R-10	.32	...	...	...	...	284.1	26.6	115.4
	R-7	.34	...	...	...	...	669.0	46.3	261.6

¹USLE, Universal Soil Loss Equation. Data calculated using 1973 SCS handbook "Rainfall-Erosion Losses From Cropland in Oklahoma."²Excludes sediment yield from gully.³Includes sediment yield from gully.⁴Total watershed area, 1.48 acres.⁵Total watershed area, 19.19 acres.

Table 9-2.—Measured sediment yields from various land uses in cropland watersheds for comparison with sediment-yield estimates by the MUSLE and soil-loss estimates by the USLE¹

Method	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Average
WATERSHED C-1, DRY COTTON, 17.83 ACRES												
Measured yield	3.9	0.3	11.1	10.8	3.8	8.2	11.5	25.2	2.2	21.0	6.5	9.5
Estimated yield, MUSLE	3.9	.2	3.5	2.3	1.9	5.5	4.3	7.0	1.1	11.8	1.8	3.9
Estimated soil loss, USLE	47.8	52.0	47.2	48.5	47.8	47.2	48.0	48.0	42.4	23.7	47.7	47.7
Measured/MUSLE × 100	100.5	205.4	317.4	477.4	200.9	148.4	267.5	361.9	205.9	177.4	368.0	257.3
Measured/USLE × 100	8.1	.7	23.6	22.3	7.9	17.4	23.9	52.6	4.6	49.4	27.5	21.6
Calculated DR	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	89.0
WATERSHED C-3, IRRIGATED COTTON, 44.26 ACRES												
Measured yield	42.9	55.6	124.6	43.5	44.1	96.5	35.9	150.0	55.2	94.3	20.1	69.3
Estimated yield, MUSLE	43.9	24.7	50.9	17.8	18.2	56.5	25.5	63.4	22.9	55.5	8.1	35.1
Estimated soil loss, USLE	125.3	136.3	132.0	135.3	137.3	137.3	130.8	130.8	137.3	136.8	63.5	134.2
Measured/MUSLE × 100	97.8	225.4	245.5	244.4	243.0	170.8	139.0	240.4	240.9	169.8	248.3	205.9
Measured/USLE × 100	34.3	40.8	94.6	32.2	32.2	70.3	26.1	114.7	40.2	68.9	31.6	53.3
Calculated DR	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	78.0
WATERSHED C-4, IRRIGATED COTTON, 29.93 ACRES												
Measured yield	10.9	18.0	55.3	16.4	32.5	54.8	22.5	118.8	30.2	146.8	14.8	47.4
Estimated yield, MUSLE	18.9	7.9	19.7	10.2	46.4	28.1	15.2	40.4	16.8	50.8	1.9	23.3
Estimated soil loss, USLE	81.7	88.9	85.4	93.0	88.6	89.4	88.6	85.4	86.3	85.9	40.7	81.3
Measured/MUSLE × 100	57.9	229.9	279.8	160.4	70.0	194.9	148.5	293.7	180.0	289.2	776.9	243.8
Measured/USLE × 100	13.4	20.3	64.7	17.6	36.7	61.3	25.4	139.1	35.0	171.0	36.5	56.4
Calculated DR	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	83.0
WATERSHED C-5, CONTINUOUS WHEAT, 12.75 ACRES												
Measured yield	0.8	1.7	0.2	0.4	2.6	12.0	1.8	10.0	1.5	16.4	2.9	4.6
Estimated yield, MUSLE	.5	.3	.2	.2	.8	4.1	3.1	2.9	1.7	3.8	.7	1.7
Estimated soil loss, USLE	16.4	17.9	16.2	16.5	17.3	16.8	18.6	16.0	17.9	13.3	8.9	16.7
Measured/MUSLE × 100	176.0	547.3	118.4	181.0	326.4	292.7	58.3	337.9	86.2	433.1	426.3	271.2
Measured/USLE × 100	4.9	9.5	1.4	2.2	15.2	71.2	9.7	62.2	8.4	123.6	32.5	31.0
Calculated DR	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	93.0

See footnote at end of table.

Table 9-2.—Measured sediment yields from various land uses in cropland watersheds for comparison with sediment-yield estimates by the MUSLE¹ and soil-loss estimates by the USLE¹—Continued

Method	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Average
WATERSHED C-6, CONTINUOUS WHEAT, 13.00 ACRES												
Measured yield tons	1.6	1.9	0.9	0.5	5.2	22.9	2.5	18.6	1.8	22.9	9.4	8.0
Estimated yield, MUSLE tons . . . . .	.9	.4	.7	.4	1.8	6.8	2.7	4.2	2.4	4.4	1.2	2.4
Estimated soil loss, USLE tons	18.6	20.3	18.4	18.8	19.6	19.0	21.1	18.1	20.3	15.1	10.1	19.0
Measured/MUSLE × 100 pct	177.0	498.7	127.8	120.3	293.6	353.3	92.3	443.5	78.4	523.5	761.2	315.4
Measured/USLE × 100 pct	8.6	9.4	5.1	2.4	26.3	120.3	11.9	103.0	9.1	152.2	93.1	49.2
Calculated DR . . . . .	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	93.0
WATERSHED C-7, MIXED ROW CROP AND ALFALFA, 26.52 ACRES												
Measured yield tons	20.7	15.9	23.6	15.8	12.0	108.4	0.9	3.4	1.5	15.3	0.6	19.8
Estimated yield, MUSLE tons	20.6	15.1	19.5	6.7	3.1	18.8	7.4	9.8	1.5	14.7	.7	16.7
Estimated soil loss, USLE tons	68.5	76.1	70.1	48.3	31.7	40.7	24.0	24.8	59.7	55.2	26.2	50.0
Measured/MUSLE × 100 pct	100.3	105.2	121.2	235.3	389.1	577.5	12.7	34.7	104.6	104.4	83.9	169.9
Measured/USLE × 100 pct	30.2	20.9	33.7	32.7	37.8	266.2	3.9	13.7	2.6	27.7	2.2	42.9
Calculated DR . . . . .	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	84.0
WATERSHED C-8, 4-YR ALFALFA-WHEAT ROTATION, 27.28 ACRES												
Measured yield tons	0.6	0.1	0.1	0.2	0.9	28.9	1.1	17.1	0.7	0.8	0.0	4.6
Estimated yield, MUSLE tons . . . . .	.3	.1	.0	.0	.5	2.9	2.3	6.7	.8	.7	.0	1.3
Estimated soil loss, USLE tons	3.2	3.2	3.2	31.7	47.4	42.7	50.1	42.0	3.2	3.2	1.5	22.0
Measured/MUSLE × 100 pct	213.7	129.9	234.2	536.6	194.5	989.5	50.2	256.2	87.2	111.4	.1	254.9
Measured/USLE × 100 pct	18.1	3.5	2.8	.1	1.9	67.6	2.3	40.7	20.7	24.5	.1	16.6
Calculated DR . . . . .	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	84.0

¹MUSLE, Modified Universal Soil Loss Equation. USLE, Universal Soil Loss Equation. DR, calculated delivery ratio using watershed area.

Table 9-3.—Measured sediment yields from various land uses in rangeland watersheds for comparison with sediment-yield estimates by the MUSLE and soil-loss estimates by the USLE¹

Method	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	Average
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WATERSHED R-5, RANGELAND, PROPERLY GRAZED, 23.72 ACRES

Measured yield	tons	1.1	0.3	1.2	0.1	0.5	0.2	1.8	0.3	1.3	0.0	0.5	0.7
Estimated yield, MUSLE	tons	9.2	.8	9.0	.5	4.8	3.5	44.4	5.9	7.1	.0	3.5	8.1
Estimated soil loss, USLE	tons	30.3	28.0	37.2	46.3	43.1	61.2	35.8	41.2	17.9	27.5	23.0	35.6
Measured/MUSLE × 100	pct	11.5	33.1	13.6	32.3	10.5	5.1	4.0	5.6	18.1	64.5	13.4	19.5
Measured/USLE × 100	pct	3.5	1.0	3.3	.3	1.2	.3	5.0	.8	7.2	.0	2.0	2.2
Calculated DR													86.0

WATERSHED R-6, RANGELAND, PROPERLY GRAZED, 27.22 ACRES

Measured yield	tons	1.6	0.4	2.7	0.3	1.4	0.7	24.9	0.9	8.1	0.2	4.5	4.2
Estimated yield, MUSLE	tons	26.6	1.7	15.0	1.2	8.5	9.9	170.5	17.6	50.5	1.5	53.2	32.4
Estimated soil loss, USLE	tons	77.9	63.7	61.2	76.1	93.7	113.5	110.7	116.6	94.4	82.9	92.5	89.4
Measured/MUSLE × 100	pct	6.2	23.0	18.2	21.7	16.7	7.5	14.6	4.9	16.0	13.2	8.4	13.7
Measured/USLE × 100	pct	2.1	.6	4.4	.3	1.5	.7	22.5	.7	8.5	.2	4.9	4.2
Calculated DR													84.0

WATERSHED R-7, RANGELAND, OVERGRAZED, 19.19 ACRES

Measured yield	tons	21.8	15.0	43.8	23.2	36.5	25.3	182.6	35.9	64.5	6.3	92.8	49.8
Estimated yield, MUSLE	tons	74.0	60.0	97.5	38.5	148.0	147.5	658.3	344.1	73.2	48.9	158.0	168.0
Estimated soil loss, USLE	tons	111.0	111.0	140.7	132.7	160.3	227.5	235.2	382.9	81.7	218.3	170.4	179.3
Measured/MUSLE × 100	pct	29.5	24.9	44.9	60.2	24.6	17.1	27.7	10.4	88.1	12.9	58.7	36.3
Measured/USLE × 100	pct	19.7	13.5	31.1	17.5	22.7	11.1	77.6	9.4	78.9	2.9	54.5	30.8
Calculated DR													88.0

WATERSHED R-8, RANGELAND, OVERGRAZED, 27.55 ACRES

Measured yield	tons	28.4	31.2	67.9	31.6	76.4	34.8	375.9	121.7	184.3	30.5	186.0	106.2
Estimated yield, MUSLE	tons	127.8	93.3	205.9	56.9	160.5	127.7	604.5	565.8	337.3	102.5	430.8	255.7
Estimated soil loss, USLE	tons	327.6	375.0	369.4	357.4	354.0	378.0	294.2	542.2	542.2	542.2	542.2	420.4
Measured/MUSLE × 100	pct	22.2	33.3	33.0	55.6	47.6	27.3	62.2	21.5	54.6	29.7	43.2	39.1
Measured/USLE × 100	pct	8.7	8.3	18.4	8.8	21.6	9.2	127.8	22.5	34.0	5.6	34.3	27.2
Calculated DR													84.0

WATERSHED R-9, RANGELAND, OVERGRAZED, 9.30 ACRES

Measured yield	tons	.....	.....	.....	.....	17.1	8.4	90.1	10.3	23.5	2.8	11.6	23.4
Estimated yield, MUSLE	tons	.....	.....	.....	.....	81.6	89.5	400.0	252.3	44.6	21.8	100.8	141.5
Estimated soil loss, USLE	tons	.....	.....	.....	.....	76.1	111.9	122.7	199.8	42.5	113.4	87.7	107.7
Measured/MUSLE × 100	pct	.....	.....	.....	.....	20.9	9.4	22.5	4.1	52.7	12.8	11.5	19.1
Measured/USLE × 100	pct	.....	.....	.....	.....	22.5	7.5	73.7	5.1	55.3	2.5	13.2	25.7
Calculated DR													98.0

¹MUSLE, Modified Universal Soil Loss Equation. USLE, Universal Soil Loss Equation. DR, calculated delivery ratio using watershed area.

Table 9-4.—Confidence limits of measured and estimated ratios and the resulting estimated yields for comparison with measured yields

Watershed and use	Method ¹	Average yield (tons)	95-pct confidence limits			
			Lower (pct)	Upper (pct)	Lower ² (tons)	Upper ³ (tons)
C-1, dryland cotton	Measured	9.5	...	...	4.3	14.7
	MUSLE	3.9	182	333	7.1	13.1
	USLE	47.7	7	36	3.3	17.2
C-3, irrigated cotton	Measured	69.4	...	...	41.8	96.9
	MUSLE	35.1	171	241	60.1	84.7
	USLE	134.2	33	73	44.3	98.0
C-4, irrigated cotton	Measured	47.4	...	...	17.0	77.8
	MUSLE	23.3	113	374	27.0	87.2
	USLE	81.3	22	91	17.9	74.0
C-5, wheat	Measured	4.6	...	...	.9	8.3
	MUSLE	1.7	164	378	2.7	6.3
	USLE	16.7	5	57	.8	9.5
C-6, wheat	Measured	8.0	...	...	1.9	14.1
	MUSLE	2.4	168	463	4.0	10.9
	USLE	19.0	12	87	2.3	16.5
C-7, mixed row crop and alfalfa	Measured	19.8	...	...	.0	40.3
	MUSLE	16.7	56	284	9.4	47.5
	USLE	50.0	0	93	.0	46.5
C-8, alfalfa-wheat, 4-yr rotation	Measured	4.6	...	...	.0	11.0
	MUSLE	1.3	65	444	.8	5.7
	USLE	22.0	2	31	.4	6.8
R-5, virgin rangeland	Measured . . . . .	.7	...	...	.3	1.0
	MUSLE	8.1	7	31	.6	2.5
	USLE	35.6	1	4	.4	1.4
R-6, virgin rangeland	Measured	4.2	...	...	.0	9.0
	MUSLE	32.4	10	18	3.2	5.8
	USLE	89.4	0	9	.0	8.0
R-7, rangeland, overgrazed	Measured	49.5	...	...	16.0	83.6
	MUSLE	168.0	20	52	33.6	87.4
	USLE	179.3	13	49	23.3	87.8
R-8, rangeland, overgrazed	Measured	106.2	...	...	33.9	178.6
	MUSLE	255.7	30	49	76.7	125.3
	USLE	420.4	4	51	16.8	214.4
R-9, rangeland, overgrazed	Measured	23.4	...	...	.0	51.3
	MUSLE	141.5	7	31	9.9	43.9
	USLE	107.7	5	46	5.4	49.5

¹MUSLE, Modified Universal Soil Loss Equation. USLE, Universal Soil Loss Equation.

²Lower confidence limits on measured yields. Lower limits (tons) for both the MUSLE and USLE calculated by multiplying average estimated yields (or erosion) by (pct) confidence limits.

³Upper confidence limits on measured yields. Upper limits (tons) for both the MUSLE and USLE calculated by multiplying average estimated yields (or erosion) by upper (pct) confidence limits.

percentage of ground cover on the rangeland. Total volume and peak rate of runoff were used in the MUSLE to estimate sediment yields for individual storms. The MUSLE afforded the opportunity to compare estimated yields, using specific storm data, with measured yields, and the USLE provided the opportunity to compare long-time average erosion estimates with measured yields.

The ratio of measured to estimated yields for both procedures is also presented in tables 9-2 and 9-3. In the case of the USLE, the ratio is the portion of the estimated erosion that was delivered from the watershed (delivery ratio). In the case of the MUSLE, the ratios represent the magnitude of over or under estimate. A delivery ratio (*DR*) calculated by using the equation $DR=54A^{-0.14}$, where watershed area (*A*) is in square miles, is also given (U.S. Soil Conservation Service 1967).

The delivery ratios calculated using watershed area were much higher than the actual USLE delivery ratios determined from measured and estimated values. Average calculated delivery ratios ranged from 78 to 93 percent, while actual average delivery ratios ranged from 2 to 56 percent. Sediment-yield estimates using the USLE and a calculated delivery ratio differed widely from measured yields from small watershed areas. For the watersheds in tables 9-2 and 9-3, the sediment yields estimated by this procedure were 1.4 to 4.5 times higher than actual yields on the cropland watersheds and 3.2 to 43.7 times higher than actual yields on the rangeland watersheds. Optimization (or fitting) was not attempted with either equation. The results are representative of those expected using available data. However, in most cases volume and peak-rate data are not available for use in the MUSLE.

Sediment yields were underestimated by the MUSLE on the cropland watersheds and overestimated on the rangeland watersheds. Average measured yields on the cropland watersheds were 1.7 to 3.2 times higher than the MUSLE estimates. On the rangeland watersheds, the average MUSLE estimates were 2.4 to 7.7 times higher than the measured values. The flat slopes on the cropland watersheds (0.2 to 0.7 percent) could account for a part of the difference between estimated yields by the MUSLE and measured yields, since none of the watersheds used in developing the equation were this flat. The cover factor used for the rangeland watersheds was untested and could also account for some of the

differences. The flat slopes and untested cover factor could also have influenced the results of the USLE estimates.

CONFIDENCE LIMITS ON EROSION AND SEDIMENT-YIELD ESTIMATES

The 95-percent confidence limits on the ratios of measured to estimated values (table 9-4) could be interpreted as the reliability of the ratios for the two procedures on the various watersheds. The confidence limits are based on 11 years of data from each watershed, except for one watershed with only 7 years of data. The average ratio should be within the limits shown 95 percent of the time. If these limits are multiplied by the average estimated yield or erosion, the results should include the average measured yield 95 percent of the time. Using this procedure, the average measured yield should range from 7.1 to 13.1 tons on the dryland-cotton watershed for the MUSLE ($3.9 \text{ tons} \times 182 \text{ percent} = 7.1 \text{ tons}$; $3.9 \text{ tons} \times 333 \text{ percent} = 13.1 \text{ tons}$). Average measured yield using the USLE should range from 3.3 to 17.2 tons ($47.7 \text{ tons} \times 7 \text{ percent} = 3.3 \text{ tons}$; $47.7 \text{ tons} \times 36 \text{ percent} = 17.2 \text{ tons}$). The confidence limits on the measured yields for the period of record are also shown in table 9-4 for comparison. The limits of the measured yield are generally greater than those of the MUSLE and are approximately equal to the USLE limits. These data indicate that average yields, calculated by multiplying the MUSLE estimates by the delivery ratio or percentage measured, do not cover the range of values observed in the measured data. This appears to be the results of consistent underestimates in years with high sediment yields and overestimates in years with low sediment yields.

SUMMARY

This research shows that the frequently used procedure of multiplying a delivery ratio by USLE estimates produces sediment yields that are too high by several orders of magnitude. The procedure is probably suitable for ranking sediment-source areas but would not be suitable for predicting sediment yields unless estimates are needed only within several orders of magni-

tude. Sediment-yield estimates by the MUSLE were also in error by several orders of magnitude. The MUSLE uses storm volume and peak rate of runoff and would logically be more suitable for estimating sediment-yield. However, it may be necessary to calibrate the equation with some data from the watersheds for which estimates are needed.

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Section 10.—Sediment Yield and Transport in Large Watersheds

INTRODUCTION

Sediment movement in the past has created, and continues to create, economic, aesthetic, and water-treatment problems for much of the Southern Great Plains. Economic damages on agricultural land include sheet, rill, gully, and channel erosion and subsequent deposition of eroded materials on slopes and alluvial areas and in channels and reservoirs. The major objective of this study was to determine, for a large river basin, changes in the downstream sediment regime attributable to floodwater-retarding structural treatment. Other objectives included determining the sources and characteristics of sediment yield, relating sediment transport in channels to channel hydraulic parameters, and studying floodwater-retarding structures to determine sediment-trap efficiency and the amount, location, and characteristics of sediment deposition.

PROCEDURE

Except for one watershed in the study reach, sediment-transport data had been collected for a few years on the watersheds before installation of the floodwater-retarding structures from 1961 to 1978. This permitted a comparison of these data with data collected after treatment.

Sediment-transport data were collected at 5 gaging sites on the Washita River (1 site was abandoned early in the study) and at 12 gaging sites on tributary watersheds (3 were discontinued in 1972 and another in 1973). The Tonkawa watershed had two gaging sites, one near the juncture with the Washita River alluvium and a second near the confluence. Transport data from these locations detected any changes occurring

in the 3-mile, flatter sloped channel reach across the Washita River alluvium, where the channel wound through a system of old Washita River oxbow lakes.

During the study, the channelization of Sugar Creek presented an opportunity to study how sediment-transport capacity varied with changes in stream slope. The first 1.5 miles above the mouth had a variable slope resulting from back-water effects of the Washita River. Therefore, a gaging site was instrumented in this lower reach, and pertinent hydraulic and sediment data were collected.

Sediment yields for the watersheds were determined by taking periodic flow samples, principally during flow events, with either manually operated or pumping-type suspended-sediment samplers. (See section 15 for a review of instrumentation developed or tested during the course of the study.) Each sample was analyzed in a sediment laboratory for total sediment concentration. For a small percentage of the samples, the amount and gradation of the sand fraction (>0.062 millimeter) was determined by wet sieving and by using the visual-accumulation-tube apparatus. In 1977, a sedigraph instrument was acquired to analyze the gradation of the silt and clay fractions of the load. Since all but two gaging sites were discontinued soon after receiving the instrument, silt- and clay-gradation data were meager.

Transport data for most stations were computed time incrementally by the continuous-concentration-curve procedure, which is considered the most accurate method. For lack of concentration data, a portion of the record at three sites had to be computed by the sediment-rating-curve procedure. A study (unpublished) showed that sediment loads computed by the sediment-rating-curve method differed from those computed by the continuous-concentration-

Table 10-1.—Annual sediment yields, in tons per acre per year, and runoff, in inches, for the gaged watersheds¹

Watershed ² /	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	Avg.
Washita R., above Anadarko, OK D.A. = 3636 mi. ²	0.56 (1.48)	0.07 (0.50)	0.23 (0.78)	0.41 (1.63)	0.03 (0.51)	0.04 (0.31)	0.25 (1.08)	0.35 (1.31)	0.03 (0.34)	0.09 (0.41)	0.04 (0.32)	0.39 (1.60)	0.39 (0.32)	0.39 (1.60)	0.39 (0.32)	0.21 (0.86)	
Washita R., above J'erden, OK D.A. = 4083 mi. ²	0.55 (1.46)	0.07 (0.51)	0.26 (0.75)	0.43 (1.55)	0.04 (0.54)	0.09 (0.32)	0.41 (1.07)	0.68 (1.29)	0.06 (0.34)	0.11 (0.39)	0.05 (0.29)	0.44 (1.52)	0.26 (0.84)	0.26 (0.84)	0.26 (0.84)	0.26 (0.84)	
Washita R., above Chickasha, OK D.A. = 4328 mi. ²	0.54 (1.46)	0.07 (0.50)	0.22 (0.70)	0.43 (1.39)	0.05 (0.53)	0.10 (0.35)	0.31 (1.00)	0.62 (1.28)	0.09 (0.39)	0.12 (0.44)	0.04 (0.29)	0.50 (1.58)	0.27 (1.17)	0.49 (2.16)	0.07 (0.69)	0.27 (1.33)	0.26 (0.95)
Washita R., above Tabler, OK D.A. = 4707 mi. ²			0.35 (0.75)	0.59 (1.40)	0.09 (0.57)	0.16 (0.41)	0.36 (1.00)	0.74 (1.29)	0.15 (0.43)						0.35 (0.84)		
Washita R., above Alex, OK D.A. = 4787 mi. ²	0.75 (1.60)	0.11 (0.55)	0.41 (0.79)	0.66 (1.39)	0.10 (0.55)	0.17 (0.42)	0.37 (1.02)	0.73 (1.34)	0.16 (0.46)	0.19 (0.53)	0.10 (0.39)	0.81 (1.91)	0.43 (1.28)	0.84 (2.39)	0.11 (0.79)	0.47 (1.37)	0.40 (1.05)
Tonkawa Cr. (Lower) D.A. = 39.3 mi. ²		0.002 (0.13)	0.002 (0.14)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.002 (0.48)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.005 (0.47)	0.003 (0.92)	0.020 (1.79)	0.006 (0.93)	0.010 (0.39)	0.004 (0.38)
Tonkawa Cr. (Upper) D.A. = 260 mi. ²	0.10 (0.98)	1.03 (1.38)	0.28 (0.86)	0.03 (0.54)	0.17 (0.54)	0.15 (0.54)	0.46 (0.83)	0.01 (1.28)	0.01 (0.33)	0.06 (0.27)	0.03 (0.48)	0.12 (1.92)	0.05 (1.48)	0.07 (2.34)	0.06 (1.37)	0.03 (0.79)	0.18 (1.03)
Sugar Creek D.A. = 2039 mi. ²	0.54 (0.36)	1.99 (2.16)	0.32 (0.61)	0.96 (0.59)	2.21 (1.37)	7.14 (2.02)	1.40 (0.73)	0.19 (0.37)	0.19 (0.37)	0.02 (0.15)	0.02 (0.15)	1.16 (1.49)	0.02 (1.49)	0.02 (1.49)	0.02 (1.49)	0.02 (1.49)	1.58 (0.99)
Delaware Creek D.A. = 40.1 mi. ²	0.25 (0.60)	0.17 (0.58)	0.00 (0.24)	0.13 (0.30)	0.19 (0.72)	0.45 (0.95)	0.03 (0.33)	0.36 (0.59)	0.03 (0.43)	0.07 (0.43)	0.42 (1.92)	0.35 (1.32)	0.30 (2.07)	0.04 (0.83)	0.93 (1.46)	0.26 (0.88)	
Salt Creek D.A. = 23.8 mi. ²				1.04 (2.32)	0.25 (0.61)	0.93 (2.54)	0.65 (2.10)	0.65 (2.05)	0.66 (0.32)	0.06 (3.15)	1.05 (3.15)	0.93 (3.29)	0.71 (4.18)	0.06 (0.68)	0.63 (1.75)	0.63 (2.09)	
Line Creek D.A. = 53.4 mi. ²	0.10 (0.39)	0.10 (0.47)	0.07 (0.45)	0.01 (0.07)	0.35 (0.33)	0.01 (0.08)	0.04 (0.55)	0.04 (0.19)	0.01 (0.91)	0.07 (0.45)	0.03 (0.45)	0.03 (0.45)	0.03 (0.45)	0.03 (0.45)	0.08 (0.39)		
West Bitter Creek D.A. = 60.8 mi. ²	1.66 (1.16)	0.35 (1.01)	1.15 (1.26)	1.11 (1.59)	1.69 (1.58)	0.18 (0.89)	1.00 (2.20)	1.17 (1.76)	1.43 (2.25)	0.44 (1.32)	4.40 (7.24)	1.98 (3.88)	1.88 (6.12)	0.04 (1.01)	0.44 (1.46)	1.27 (2.32)	
East Bitter Creek D.A. = 35.1 mi. ²	2.90 (2.39)	2.06 (2.15)	1.77 (1.88)	3.02 (1.85)	0.29 (1.43)	2.00 (3.03)	0.83 (1.56)	1.85 (2.57)	0.43 (1.91)	9.64 (9.95)	1.13 (3.47)	2.59 (6.19)	0.08 (1.39)	1.40 (1.72)	2.14 (2.96)		
Little Washita R. D.A. = 207.7 mi. ²	3.23 (1.70)	1.29 (1.25)	0.23 (0.66)	0.49 (0.69)	1.17 (1.39)	2.32 (1.84)	0.29 (0.70)	1.06 (1.16)	0.90 (1.10)	4.00 (4.51)	1.57 (2.54)	3.50 (4.44)	0.55 (1.76)	0.55 (1.76)	1.33 (2.02)	1.57 (0.84)	
Big Dry Creek D.A. = 7.57 mi. ²	0.24 (0.31)	0.45 (0.64)	0.14 (0.30)	0.37 (1.63)	1.27 (2.64)	0.55 (1.83)	0.17 (1.34)	0.55 (2.89)	0.17 (1.34)	0.55 (2.89)	0.55 (2.89)	0.55 (2.89)	0.55 (2.89)	0.47 (1.45)			
Little Dry Creek D.A. = 0.88 mi. ²	0.15 (0.31)	0.28 (0.36)	0.43 (0.89)	0.25 (0.86)	0.25 (0.91)	0.25 (1.23)	0.25 (1.06)	0.25 (1.23)	0.33 (1.23)	0.63 (1.06)	0.63 (1.06)	0.63 (1.06)	0.63 (1.06)	0.63 (1.06)	0.33 (0.89)		
Winter Creek D.A. = 33.3 mi. ²	6.61 (2.88)	1.99 (2.37)	0.35 (1.39)	0.58 (1.52)	0.98 (2.48)	1.51 (3.71)	1.24 (3.01)	0.85 (2.83)	0.78 (3.02)	3.02 (3.85)	1.91 (1.85)	0.56 (1.85)	0.27 (1.85)	0.26 (1.86)	0.56 (1.86)	1.50 (3.23)	

¹/ Runoff data are in parentheses.²/ D.A., drainage area.

curve method, the maximum differences being about ± 30 percent.

Location of the intake nozzle on the manually operated suspended-sediment samplers prohibited sampling that part of the flow near the bed. The resulting unmeasured load consisted of bed-load, those particles moving along in close proximity to the bed, and a portion of the suspended load. Only two procedures were available to predict unmeasured load, the modified Einstein procedure (Colby and Hubbel 1961) and the Colby mean-velocity procedure (Colby 1957). Because there was disagreement in the unmeasured loads predicted with the two methods, a study was initiated to determine whether either of the methods could be used exclusively. The study consisted of taking numerous point velocities and point sediment samples throughout the flow cross section during selected flows at the Washita River gaging sites. The sediment samples were analyzed for percentages of silt and clay and for percentages of various sand-particle sizes. Results of the study are given in this section under "Unmeasured-Load Research."

Because the particle-size distribution of the streambed material was needed to make computations with the modified Einstein procedure and with the various sediment-transport equations, several bed-material samples were taken and analyzed for those stations that had a significant amount of unmeasured load or bed-material load. These results are given in this section under "Bed-Material Research."

Sedimentation ranges were determined and documented on 14 floodwater-retarding structures. Sediment-trap efficiency was studied at two reservoir sites, one where long-term trap efficiency was determined and another where instrumentation was such that trap efficiency could be determined for each flow event as well as for long periods of time.

MEASURED SEDIMENT YIELDS

Table 10-1 shows annual and average annual yields for the watersheds in the study area. The range of average annual yields was surprisingly large, 0.004 to 2.14 tons per acre per year, more than a 500-fold difference. An eightfold to tenfold difference in average annual yields existed even for adjacent watersheds. These results suggest

that caution should be exercised in transposing known yield data to other watersheds. Care must be taken to see that close watershed similarities exist, including infiltration rate, soil texture, land use, slope of the main channels, precipitation, etc., before a valid transposition can be made.

Table 10-1 also illustrates that for any given watershed the range of annual yields is commonly tenfold for large watersheds and even larger for tributary watersheds, which exemplifies the problem determining long-term yields with measured data. For reliable estimates, the data collection should be continued a minimum of 3 to 5 years. The precipitation for the 3- to 5-year period should be compared with the long-term precipitation, and if sufficiently different, the sediment yield should be adjusted by some scheme. The curvilinear relation of sediment yield versus either precipitation or discharge appears useful. The data should be in storm or monthly increments, and where the record length is sufficient a seasonal trend is usually apparent.

EFFECT OF WATERSHED TREATMENT ON SEDIMENT YIELDS

Eight tributary watersheds in the study area were treated with floodwater-retarding reservoirs. Sediment-yield reductions caused by the reservoirs were determined by making double-mass plots of sediment yields from treated versus untreated watersheds. The reductions for five watersheds ranged from 48 to 61 percent (table 10-2), but there were no detected reductions for Little Washita River, East Bitter Creek, or West Bitter Creek. Also, a reduction in sediment yield could not be detected for the Washita River after the tributary watersheds were treated with reservoirs. This suggests additional uncertainty in predicting yield changes for those pollutants transported principally through attachment to sediment particles.

There is no conclusive theory thus far explaining why some treated watersheds had large reductions in sediment yield and others had none. To research this anomaly, one of the physically based, distributed-parameter sediment-yield models, such as the Colorado State University model (Simon et al. 1975), will be used initially. This model predicts runoff and erosion for time and areal increments and charts the progression

Table 10-2.—Sediment-yield reductions on watersheds treated with floodwater-retarding reservoirs

Watershed	Area (acres)	Reservoirs			
		Total No. ¹	Dates Const. ¹	Treated area ¹ (pct)	Sediment-yield reduction (pct)
Sugar Creek	128,960	25	1962-63	40	² 61
Winter Creek	21,310	9	1965-66	56	60
Big Dry Creek	4,845	5	1966	63	51
Little Dry Creek	563	1	1966	60	48
Tonkawa Creek	16,640	12	1968-70	68	² 48
Little Washita River . . .	132,930	39	1969-77	46	0
East Bitter Creek	22,460	7	1973-74	21	0
West Bitter Creek	38,910	11	1972-75	29	0

¹Structure data that were completed when sediment-reduction analyses were made.

²Determined with sediment predictions by the flow-duration, sediment-rating-curve method.

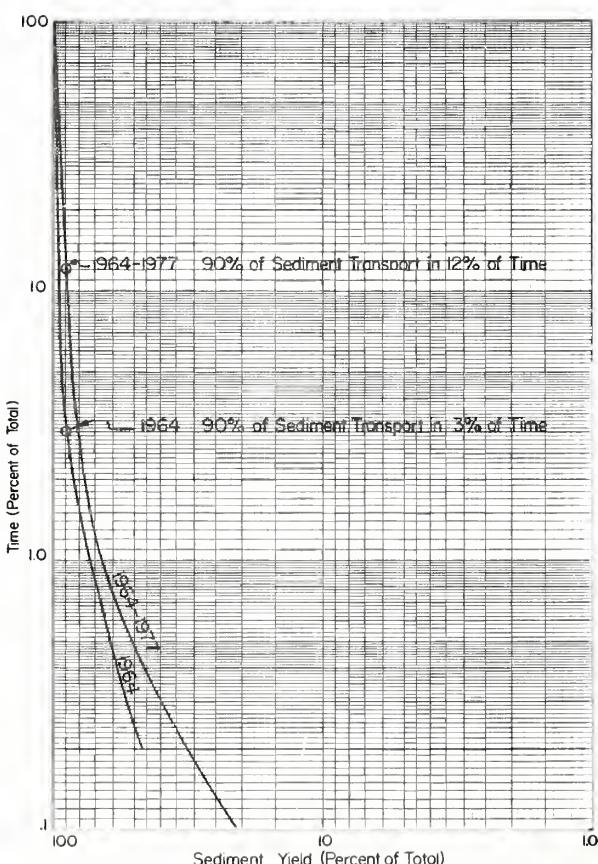


FIGURE 10-1.—Percentage of sediment yield versus percentage of time for Little Washita River.

(or deposition) of sediment down slopes and through upland and alluvial channels.

TIME DURATION OF SEDIMENT YIELDS

An example of the time distribution of the sediment yield from the Little Washita River, with a drainage area of 208 square miles, is shown in figure 10-1. During the 14-year period, 90 percent of the yield occurred in 11.5 percent of the time. In 1964, when a large storm accounted for much of the yield, 90 percent of the yield occurred in only 3 percent of the time. As subwatersheds in any basin get smaller, the bulk of the yield occurs in a smaller percentage of time. This points out the necessity of automatic sampling equipment for data collection on small watersheds. Table 10-3 shows the time distribution of sediment yield for various watersheds.

UNMEASURED-LOAD RESEARCH

When manually operated suspended-sediment samplers are used, a part of the sediment load near the bed cannot be sampled. As previously stated, an unmeasured-load study was made because rates computed by the only two methods, the modified Einstein procedure (Colby and Hubbel 1961) and the Colby mean-velocity method (Colby 1957) generally did not agree (Allen and

Table 10-3.—Time distribution of sediment yield for various watersheds

Watershed	Percentage of time for—				
	>50 pct of load	>60 pct of load	>70 pct of load	>80 pct of load	>90 pct of load
MAIN RIVER STATIONS					
Washita River:					
At Anadarko	1.3	1.9	2.7	3.9	6.6
At Verden	1.4	2.0	3.0	4.6	8.0
At Chickasha	2.1	2.9	4.2	6.3	11.1
At Alex	2.2	3.2	4.9	7.8	15.0
TRIBUTARY STATIONS					
Tonkawa Creek	0.2	0.3	0.4	0.8	1.8
Sugar Creek . . . . .	.2	.4	.9	.8	8.8
Delaware Creek . . . . .	.3	.5	1.0	4.4	2.3
Salt Creek . . . . .	.4	.6	.8	1.2	2.0
West Bitter Creek . . . . .	.3	.5	.7	1.1	1.9
East Bitter Creek . . . . .	.3	.5	.7	1.1	2.2
Little Washita River . . . . .	.5	.7	1.3	2.6	11.5

Welch 1967a). First, the field-collected concentration-distribution data were fitted to the theoretical sediment-distribution equation used in the modified Einstein procedure. The equation is

$$\frac{c}{c_a} = \left(\frac{d-y}{y} \cdot \frac{a}{d-a} \right)^z,$$

where c and c_a =concentrations of suspended sediment at distances y and a above the bed, respectively,
 d =stream depth,

$$z = \frac{v_s}{ku^*},$$

v_s =settling velocity of the sediment grains in the flow,

k =von Karman constant,

$u^* = \sqrt{gdS}$ =shear velocity,

S =energy gradient,

and g =gravity acceleration constant.

Generally, the field-concentration data fit the power function type of equation (see examples in figure 10-2). The z power values developed from field data (the slope of the lines in figure 10-2) did not agree with z values computed with $z=v_s/ku^*$ (Allen and Welch 1967b). The empirically derived

z values used in the modified Einstein procedure also did not agree with those developed from field data.

The velocity distribution of the field data did not make good straight line plots (fig. 10-3) and, therefore, did not fit the logarithmic velocity equation used in the modified Einstein procedure. Also, von Karman k values determined for the field data were as much as 4 times greater than the commonly used $k=0.4$.

Faced with these problems, a new method for determining unmeasured loads was devised (Allen and Barnes 1975) to evaluate the accuracy of the other two methods. The method extrapolates concentration and velocity measurements, made just above the unmeasured zone, into the unmeasured zone. The theoretical concentration equation was used to extrapolate the concentration data, and a power function equation that fit the data well below middepth was used to extrapolate the measured velocity data. The new method showed that the modified Einstein procedure was more accurate than the Colby method and was judged sufficiently accurate for use in watersheds of the Southern Great Plains. Therefore, the modified Einstein procedure was used to compute unmeasured load for the sediment-yield data shown in table 10-1.

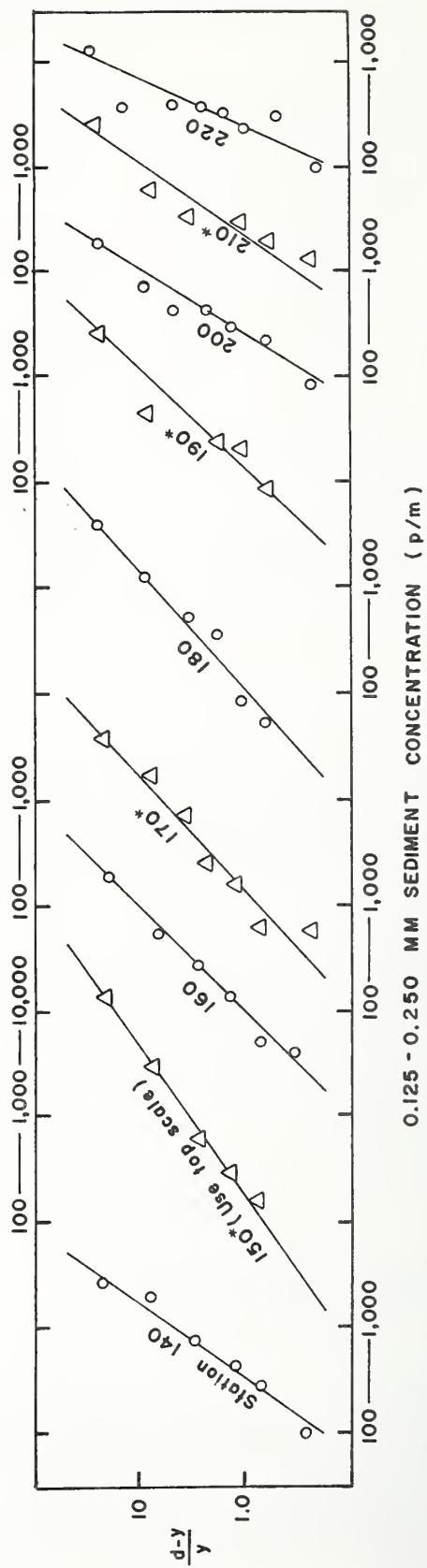
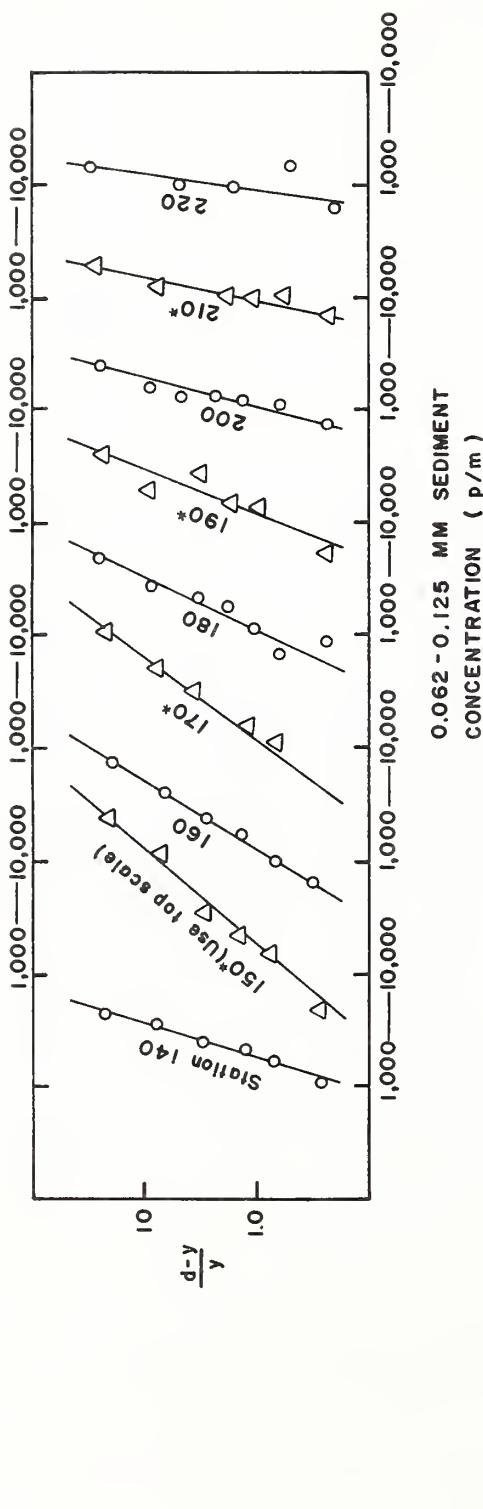


FIGURE 10-2.—Verification of the power relation in the sediment-distribution equation with Washita River field data. Numbers on lines are location distances, in feet, across the gaging site. Use top concentration scale for numbers followed by an asterisk.

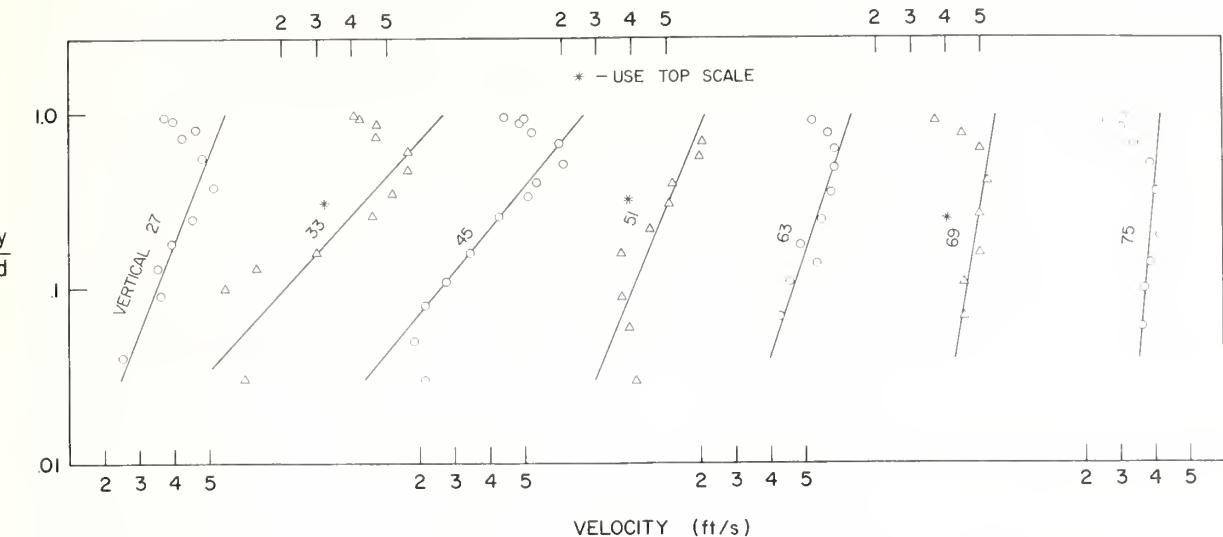


FIGURE 10-3.—Washita River field data showing the invalid relation of velocity and the log of dimensionless depth y/d . Numbers on lines are location distances, in feet, across the gaging site. Use top velocity scale for numbers followed by an asterisk.

BED-MATERIAL RESEARCH

Early in the study, a yearly sampling of the bed material in channels showed that changes in particle-size distribution occurred from year to year. To further understand the changes, the bed at the Washita River gaging site at Verden, Okla., was sampled several times during the large flow event of November 6-12, 1964. Figure 10-4 shows that the mean bed particle size (D_{50}) became progressively smaller until the final sampling, when a reversion to slightly coarser particles occurred. A time serial comparison of the gradation of the bed with that of the suspended material showed a similar trend. It appears that during flows large enough to "work" the bed, a continual exchange occurred between sediment particles in suspension and those in the first few tenths of a foot of the streambed.

Several computations with the modified Einstein procedure, made by varying the bed gradation and holding all other variables constant, showed that the total unmeasured load remained about the same. Increasing the percentage of a certain bed particle size only increased the prediction of that size in the unmeasured load. Therefore, an intensive bed-sampling program was deemed unnecessary.

CHANNEL SLOPE AND ROUGHNESS

The Sugar Creek gaging site near the Washita River confluence had a water-surface and slope measuring instrument in addition to the other stream-gaging instrumentation. On the rising side of the flow event of May 5, 1969, when the discharge was 490 cubic feet per second, the velocity was 2.7 feet per second, the depth was about 3 feet, and the slope was 0.0010 foot per foot. Later in the flow event, when the discharge was 1,440 cubic feet per second, the velocity was 7.2 feet per second, the average depth was about 5 feet, and the slope had increased to 0.0012 foot per foot. At the first slope measurement, the computed Manning n value was 0.033. At the next slope measurement, the Manning n value had decreased to 0.018. These computations illustrate that on this sandy channel a discontinuous discharge-versus-stage phenomenon occurs. At some depths of flow, two different discharges can occur, the "high phase" discharge and the "low phase" discharge. The "high phase" discharge is roughly equal to twice the "low phase" discharge. This phenomenon is troublesome in computing accurate discharge records and may have contributed to the excessive bank erosion on Sugar Creek.

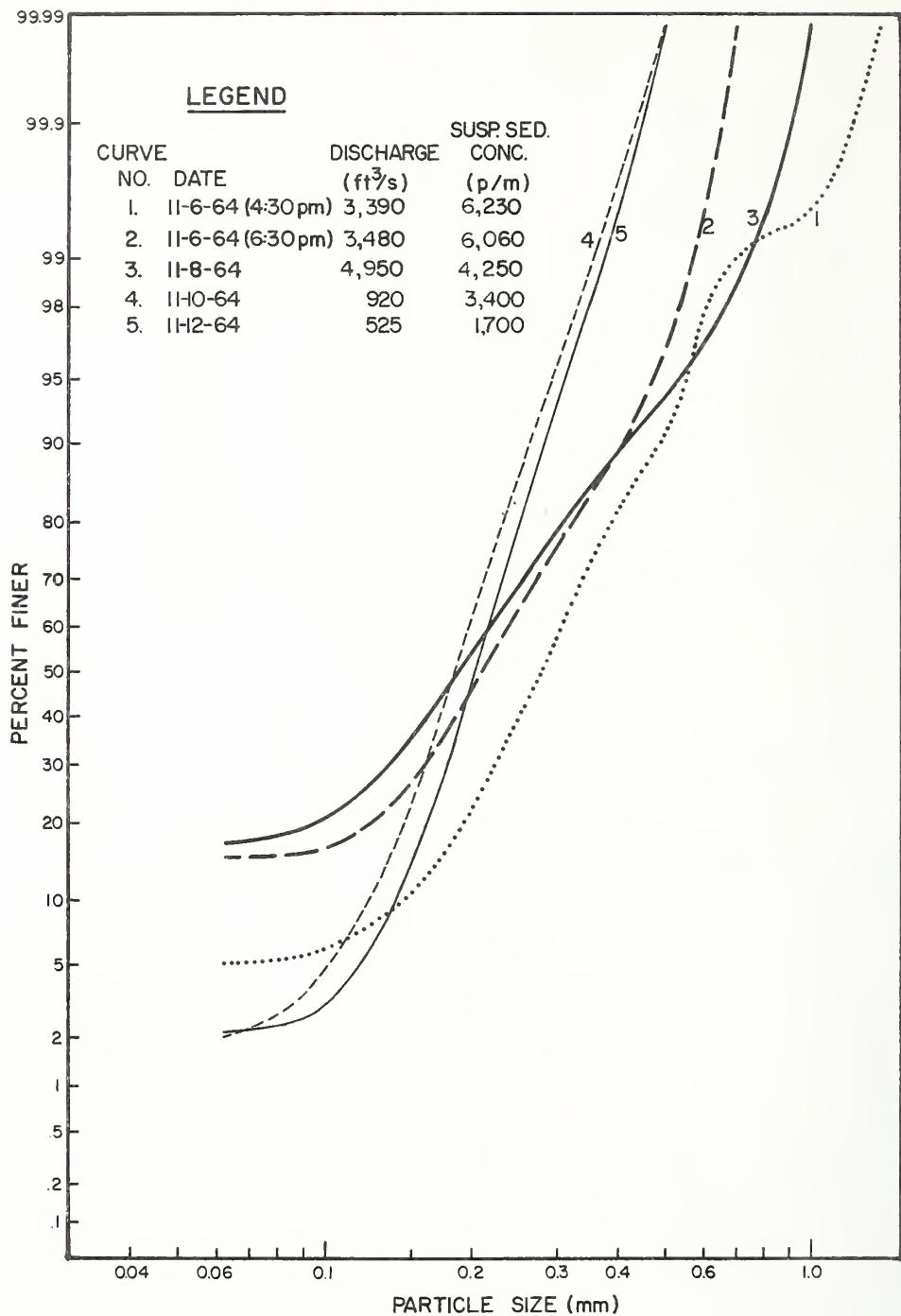


FIGURE 10-4.—Particle-size distribution of bed material for the Washita River at Verden.

SEDIMENT-TRAP EFFICIENCY OF FLOODWATER-RETARDING STRUCTURES

At floodwater-retarding structure 7 on Winter Creek (fig. 2-1), records of sediment outflow and deposition were kept from 1967 to September 1974. The outflow for the 8-year period was 270 tons. The inflow was 5,077 tons (4,807 tons from the sedimentation survey plus 270 tons of outflow). This gave a trap efficiency of 95 percent. Although a rigorous analysis of rainfall and runoff was not made, this 8-year period appears to have been below average in runoff. Therefore, the 95-percent trap efficiency may be biased and slightly high.

Using the above reservoir depositional data, the sediment yield during the 8-year period for this 750-acre watershed was 0.85 ton per acre per year, which was slightly lower than the 1.2 tons per acre per year for the entire Winter Creek watershed. Practically all the watershed was lightly grazed, formerly cultivated rangeland on which hydrologic cover generally improved from poor to fairly good during the research period. Although the upper part of the watershed was severely gullied, little of this eroded material appeared to be reaching the reservoir.

Trap-efficiency data were also obtained at reservoir 3 (fig. 2-1) on West Bitter Creek from 1975 to 1980. Sediment inflow and outflow were measured at this site, as well as reservoir deposition, so that trap efficiencies on an individual storm basis could be determined. Trap efficiencies were inversely related to the volume of main-channel water inflow and ranged from 100 percent for small flow events that did not spill to 70 percent for large flow events. A statistical regression relating trap efficiencies to main-channel inflows and also ratios of the total inflow to main-channel inflow explained 67 percent of the variation.

The overall trap efficiency at this reservoir was much lower than at the other reservoir (structure 7). The lower trap efficiency was caused by active erosion sources such as gullies and an unpaved road near the reservoir and also by berms within and parallel to the reservoir that delivered the side-source sediment to a point near the principal spillway. Such berms appear practical for lowering the trap efficiency at many completed sites that are experiencing excessive sedimentation.

BED-MATERIAL TRANSPORT EQUATIONS

Numerous equations have been developed to predict sediment transport in streams. Some contain graphical elements but all are called equations in this discussion. Such equations have been used extensively in planning river regulation projects and channel modifications. Under altered flow and sediment regimes, the equations assist with channel scour or fill estimates so that ultimate streambed elevations and slopes can be approximated. Similarly, the equations are useful in designing stable channels that must transport sediment. Some equations are being used in the newer physically based sediment-yield watershed models for computing sediment transport in channels and overland flow. For watersheds with coarse-textured soils and main channels with sandy beds, watershed sediment yield may be quickly approximated with such equations.

Table 10-4 lists many of these equations along with their principal type and dates of introduction. Although the equations are not included, a reference is given for each. For user convenience, the compilation by Shulits and Hill (1968) is used as a reference wherever possible. Because of the experimental data used, these equations probably best predict bed-material transport, i.e., the movement of those size particles predominating in the shifting portion of the streambed. Bed-material transport (or load) consists of bedload, those particles moving in the close proximity of and supported by the streambed, and suspended bed-material load, those particles suspended by the flow turbulence and found anywhere in the flow cross section—even at the surface when the turbulence is sufficient.

Except for the Laursen (Shulits and Hill 1968) equation, none of the equations listed predict wash load, the movement of finer particles (usually assumed to be silt and clay) not found appreciably in the shifting portion of the streambed. Some transport equations, such as the Rottner (Shulits and Hill 1968), Meyer-Peter and Muller (Shulits and Hill 1968), and Kalinske (Shulits and Hill 1968), were not included in table 10-4 because they best predict only the bedload component.

Some of the equations, such as the Schoklitsch (Shulits and Hill 1968), are simple and predict sediment transport with as few as two variables; other equations are more complex. For instance,

Table 10-4.—Equations for predicting transport of bed material

Type	Equation	Year introduced	References
Discharge.....	Schoklitsch	1934	Shulits & Hill (1968).
	Meyer-Peter	1934	
	Casey	1935	
	Haywood	1940	
	Schoklitsch	1943	
Tractive force	Straub-DuBoys	1935	Shulits & Hill (1968).
	U.S. Waterways Exp. Stn.	1935	
	Shields	1936	
	Elzerman and Frijlink	1951	
Dimensionless parameter.	Laursen	1957	Shulits & Hill (1968).
	Engelund and Hansen	1967	Engelund & Hansen (1967).
	Ackers and White	1973	Ackers & White (1973).
Velocity	Colby	1964	Colby (1964).
Einstein	Einstein	1950	Einstein (1950).
	Toffaleti	1968	Toffaleti (1968).
Stream power	Bagnold	1966	Bagnold (1966).
	Yang	1972	Yang (1972).

the Einstein procedure (Einstein 1950) requires about 15 flow and sediment input variables and about 40 other computed variables to determine a sediment transport rate.

One variable common to all equations is the particle size (or sizes) of the streambed sediment. Some equations were developed using uniform-size sediments and others were developed with graded sediments. Both types of equations are being used, however, to predict transport in natural streams.

Some of the equations, such as the Schoklitsch (Shulits and Hill 1968), Haywood (Shulits and Hill 1968), and Colby (Colby 1964), are empirical, having coefficients and exponents determined graphically or statistically. Many of the others, including Straub-DuBoys (Shulits and Hill 1968), Einstein (Einstein 1950), and Bagnold (Bagnold 1966), contain various theories. However, even the equations based on theory have empirical elements, which possibly explains why these equations generally predict no more accurately than those that are entirely empirical.

There has never been a comprehensive study to

determine the prediction accuracy of these equations for the range of conditions found across the United States, but several studies, using a few equations and a limited range of data, have shown that prediction accuracy is generally unsatisfactory. Figures 10-5 and 10-6 show the results of one of these studies for two streams in the Southern Great Plains. It was assumed that the equations predicted the sand fraction of the load, and therefore, predictions were compared with measured sand transports. For the Little Washita River near Ninnekah, Okla. (fig. 10-5), with a drainage area of 208 square miles, predictions by the six selected equations at low transport rates were about double the measured rates and at high transport rates were about half the measured rates. For the Washita River at Alex, Okla. (fig. 10-6), with a drainage area of 4,787 square miles, predictions with each equation were consistently high or low and ranged from roughly two times too high for the Toffaleti (Toffaleti 1968) procedure to five times too low for the Schoklitsch (Shulits and Hill 1968) equation.

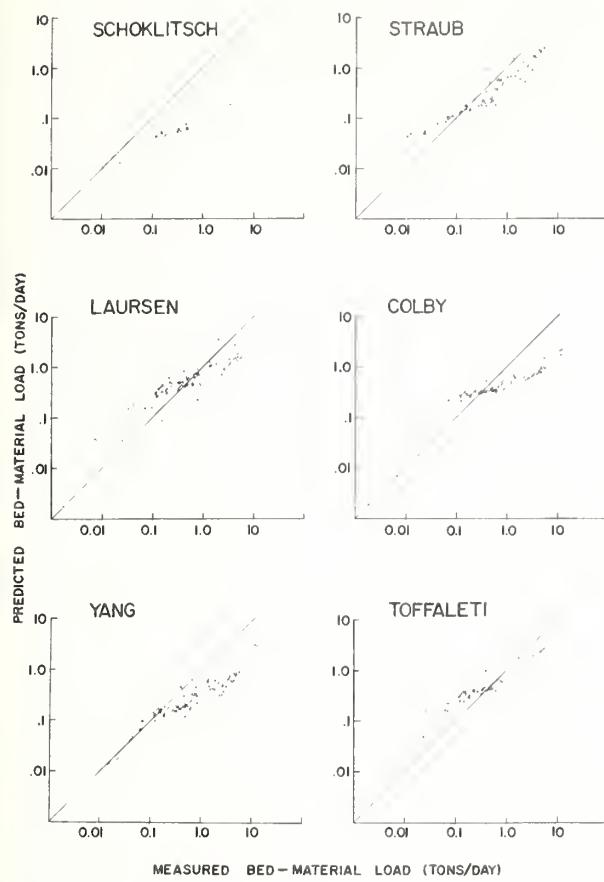


FIGURE 10-5.—Predicted and measured bed-material transports for the Little Washita River.

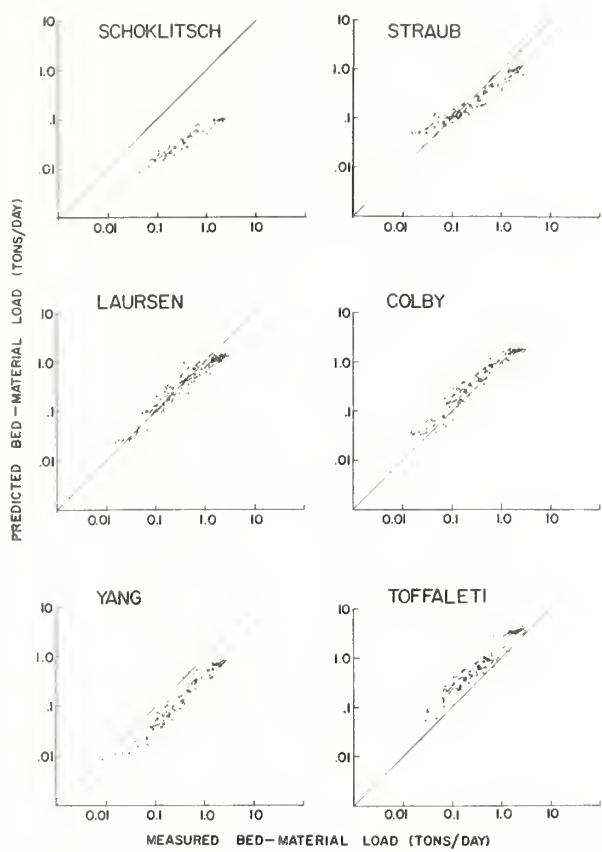


FIGURE 10-6.—Predicted and measured bed-material transports for the Washita River at Alex.

MODELING SEDIMENT YIELDS FROM WATERSHEDS

An ultimate goal of most sediment-monitoring programs today is to develop mathematical models of sediment yield from watersheds. Such models could help in the design of reservoirs by computing the sediment storage requirement. The models would also be extremely useful in land-use planning and in the control and regulation of environmental pollution by predicting not only sediment yields under various land uses and treatments but also by assisting in the prediction of chemical pollutants, such as plant nutrients, heavy metals, and pesticides, that are mainly transported while attached to soil particles.

Two tributary watersheds were modeled on an individual basis. This initial approach allowed better definition of the effects of such variables as rainfall energy, rainfall intensity, antecedent

moisture index, and the annual rangeland-cover cycle. The effects of these variables might have been masked if a universal model had been first attempted in which slope, soil type, and land use were included. With regressional techniques, 19 variables, including flow, precipitation, rangeland cover, and antecedent precipitation, were related to storm sediment yields. Analysis of West Bitter Creek data showed that sediment yield was strongly related to surface runoff ($r=0.97$) and that no improvement in the correlation was gained by adding other variables. On East Bitter Creek, however, a predictive model based on surface runoff, although good for small- and intermediate-size events, was poor for the larger storms. Great improvement was gained for this watershed by adding the following variables: duration of flow, amount of rangeland cover, 1- and 2-year antecedent precipitation, and the product of rainfall energy and maximum 15-minute intensity.

Empirical models such as those above have a severe limitation. Although they may predict quite accurately for the area for which they were developed, they usually predict poorly for dissimilar watersheds in other areas. In the past few years, newer models have been developed that determine runoff and sediment yield with relations that describe the physical processes. In determining runoff, the processes of rainfall interception, rainfall infiltration, and excess-rainfall routing are used. In determining sediment yield, the processes of detachment by rainfall, detachment by overland flow, transport by overland flow, and transport by channel flow are used. These models have the potential for more universal application than do the empirical models. In addition, these models usually use distributed parameters rather than parameters lumped for the whole watershed. This permits runoff and sediment-yield generation on a point-by-point basis, thus adding to their prediction potential.

A model of this type developed at Colorado State University (Simons et al. 1975) was initially investigated for a small 19-acre watershed. Predicted runoff rates and volumes were extremely low, only about one-tenth of the measured data. Because the infiltration procedure seemed illogical, it was replaced by an empirical relation of infiltration versus soil moisture. This change greatly improved runoff prediction accuracy. With the exception of the infiltration-routine replacement, the runoff portion of the model was fully deterministic. However, the sediment portion required calibration of two parameters. This calibration was not accomplished, but runs were made using values determined by personnel at Colorado State University for two U.S. Forest Service watersheds in northern Arizona. Sediment predictions were about 100 times too high. These results indicate that these parameters are very sensitive and suggest that predicted sediment yields will not be as accurate as runoff prediction.

SUMMARY

Sediment-transport data collected at 5 gaging sites on the Washita River and 12 sites on tributaries had a wide variation. Annual sediment yields at a given site varied by tenfold, and average annual yields between gaging sites

varied by 500-fold. An eightfold to tenfold difference occurred even for adjacent watersheds.

Five tributary watersheds treated with floodwater-retarding structures had sediment-yield reductions ranging from 48 to 61 percent. No sediment reductions were detected after treatment of three other tributary watersheds and the Washita River; this anomaly is not understood and will require further research.

A time-distribution analysis of sediment at each gaged watershed showed that most of the sediment yield occurred in a short period of time. For five tributaries, 90 percent of the yield occurred in about 2 percent of the time. As watersheds get smaller, the bulk of the yield occurs in a shorter period of time. This characteristic illustrates the necessity of automatic sediment-data collection equipment for intermediate- and small-size watersheds.

Research of unmeasured sediment load showed that field data generally fit the theoretical sediment-distribution equation $c/c_a = [(d-y)/y] \times [a/(d-a)]^z$, except for the exponent, z . The commonly used logarithmic velocity-distribution equation poorly fit the field data. An accurate unmeasured load procedure was developed to evaluate other existing procedures. This procedure uses velocity and concentration data, collected just above the unmeasured zone, and valid functions to extrapolate these parameters into the unmeasured zone. The new procedure showed that the modified Einstein procedure was more accurate than the Colby mean-velocity procedure.

Year-to-year differences in the particle-size distribution of bed material in the Washita River prompted a study of bed material during a large flow event. The bed particles became progressively finer during the event until the last sampling, when a reversion to a coarser size occurred. The gradation trend of the bed roughly followed that of the suspended load. The changes in bed-material size did not significantly alter the amount of unmeasured load computed with the modified Einstein procedure.

Discharge, depth, and slope measurements taken during a large flow at a wide, recently dredged sand-bed stream indicated that the phenomenon of discontinuous discharge versus stage had occurred. As the flow increased from 490 to 1,440 cubic feet per second, Manning n values decreased from 0.033 to 0.018. Although the data collected were untimely to best illustrate

the phenomenon, studies at other locations showed that "upper phase" discharges were about double "lower phase" discharges for the same depth of flow.

A sediment-trap efficiency of 95 percent was determined for floodwater-retarding structure 7 on Winter Creek. Precipitation for the 8-year data-collection period was slightly below average. Therefore, runoff may have been below average and the 95-percent trap efficiency slightly high. The watershed is in the Cross Timbers land resource area (fig. 2-6) and has fairly good hydrologic cover. Its measured sediment yield was 0.85 ton per acre per year.

A study comparing bed-material loads that were predicted using six well known equations with measured bed-material loads showed generally poor agreement. The Schoklitsch, Straub-DuBoys, Laursen, Colby, Toffaleti, and Yang equations were used. At one gaging site, predicted rates with the equations were about 2 times too high at high transport rates and about half the measured rates at low transport rates. At another gaging site, predictions for each equation were consistently high or low and ranged from 2 times too high for the Toffaleti equation to 5 times too low for the Schoklitsch equation.

Two watersheds were modeled individually for sediment yield. For one watershed, sediment yield was strongly related to surface runoff, and no improvement was gained by adding other watershed variables. For another watershed, a prediction model based on surface runoff, although good for small- and intermediate-size runoff events, was poor for the larger storms. Great improvement was gained by adding the following variables: duration of flow, amount of rangeland cover, 1- and 2-year antecedent precipitation, and the product of rainfall energy and maximum 15-minute intensity.

One of the newly developed physically based, distributed-parameter watershed models was investigated using data from a 19-acre watershed. Initially predicted runoff values were extremely low, but runoff predictions were generally good when the infiltration routine was replaced with a calibrated empirical routine. The sediment prediction part of the model, which required calibration of two parameters, was not fully investigated.

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Section 11.—Channel Stability

INTRODUCTION

Beginning in the late 1930's, flood flows and excessive sediment loads damaged many stream channels in the Southern Great Plains. Damages included sediment deposition, bank erosion, excessive widening, and accelerated meandering. Resulting economic losses included not only the permanent loss of productive agricultural alluvial land but also extensive damage to bridges, roads, and other structures, losses amounting to millions of dollars.

The watershed flood-retarding programs of the Soil Conservation Service (SCS) prompted a request to determine the effects of the programs on the behavior and stability of channels in the Washita River basin. Other objectives included relating channel shapes to the flows and sediment regimens and to the channel environs of geology, soils, vegetation, and ground water; developing prediction methods so that findings could be transferred to other areas; and determining the effectiveness of the several bank protection methods in use in the Washita River basin.

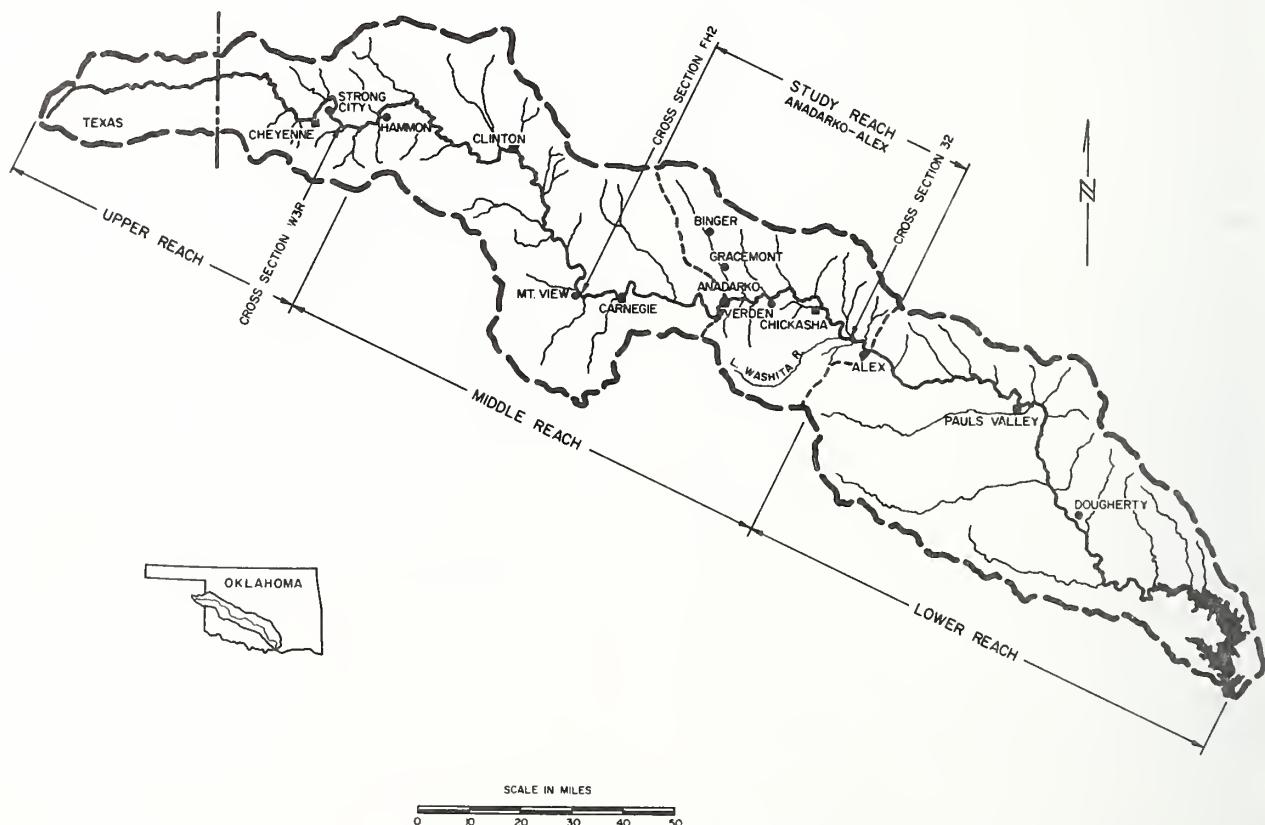


FIGURE 11-1.—Location within Washita River basin of reaches used for channel behavioral study.

PROCEDURE

The general plan was to compare channel behavior on the main stem of the Washita River before and after the installation of upstream flood-control structures. Five short-channel study reaches, based upon geological differences, were selected on the Washita River. These reaches were located within a few miles of an Agricultural Research Service (ARS) flow- and sediment-measuring station or a U.S. Geological Survey (USGS) flow-measuring station, so that flow- and sediment-transport data would be available. However, contracts with USGS to collect sediment data at three sites were never completed. Other data to be collected included water-surface gradients, channel cross-sectional geometry, particle sizes of bed and bank material, and bank vegetation types and amounts.

Several problems with the experiment became apparent early in the study. During major runoff

events, all available manpower was used at the stream gaging stations, thus leaving no one to visit the study reaches to make the needed observations. Much of the Washita River channel was already undergoing a major morphologic change, and no provision had been made to differentiate the effects caused by large reservoirs from those caused by floodwater-retarding reservoirs.

Because of these problems, two additional study reaches were established on gaged major-tributary watersheds that contained no major reservoirs, and cross sections were established about every half mile along the Washita River within the 1,130-square-mile Anadarko-to-Alex study reach. Data on past channel behavior and on some geomorphic history of the Washita River were also compiled.

The research was terminated in 1972 in a research realinement influenced by declining interest in channels and increasing interest in environmental pollution.

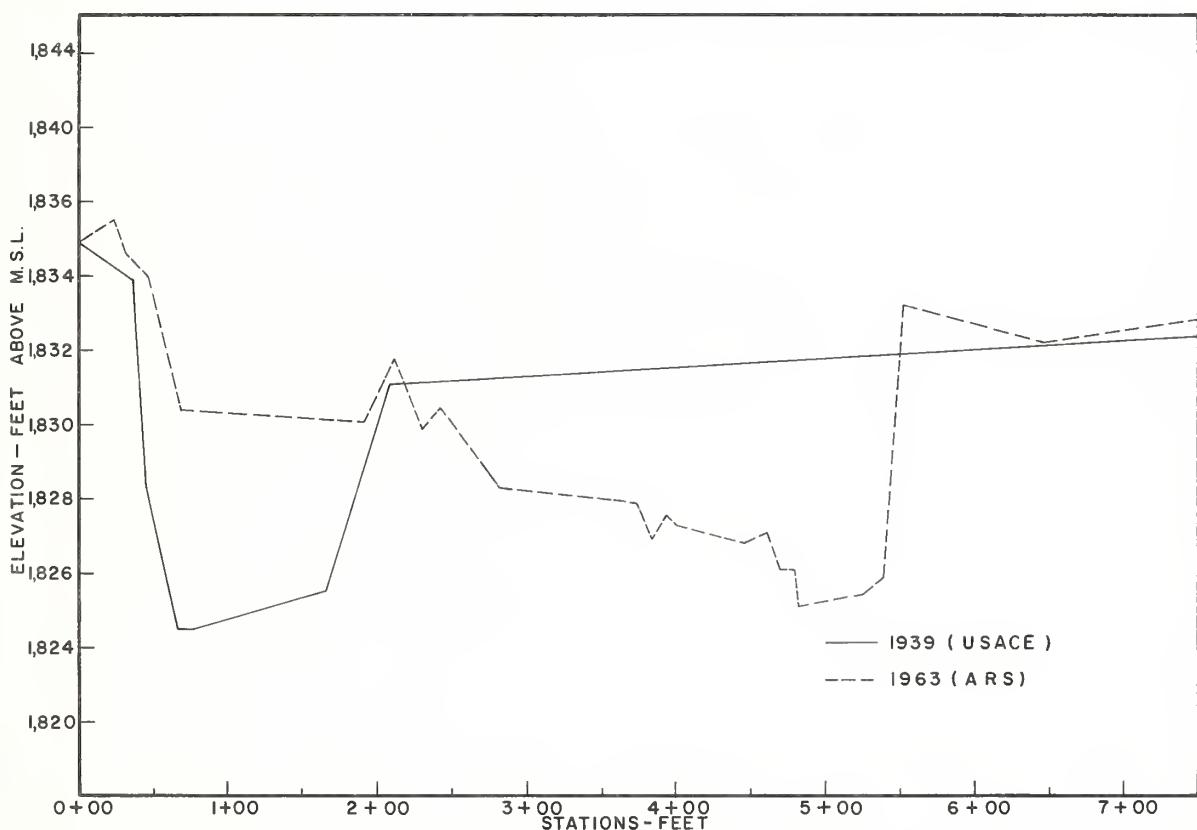


FIGURE 11-2.—Cross section W3R on Washita River near Strong City, Okla. USACE, U.S. Army Corps of Engineers.

RECENT CHANNEL BEHAVIOR

Because wheat and cotton prices were high about the time of World War I, considerable rangeland in the Washita River basin was converted to cropland. Much of this land was steep and highly erodible. However, in the Washita River and its major tributaries excessive sediment and channel problems did not materialize for many years because of a lag in the progression of sediment and an absence of large runoff events.

In this channel behavioral study, the Washita River basin was divided into upper, middle, and downstream segments. Figure 11-1 shows these and other features pertinent to the discussion. A large flood on the upper segment in 1934 (locally called the Hammon flood) extensively damaged uplands, alluvium, tributary channels, and the Washita channel downstream to Hammon, Okla. Formerly narrow, deeply incised channels (described by older residents) became clogged with sediment and widened as severe bank ero-

sion occurred. A cross section surveyed in 1939 by the U.S. Army Corps of Engineers shows the damaged Washita River channel near Strong City, Okla. (fig. 11-2). In 1963, a resurvey of this cross section by ARS (fig. 11-2) showed the extensive channel migration that had occurred, causing land owners and the U.S. Army Corps of Engineers to install numerous bank protection devices.

The middle segment of the Washita River, from Hammon to the mouth of the Little Washita River, experienced little change for reasons not fully understood. A cross section near Mountain View, Okla. (fig. 11-3), shows that, although some channel fill and alluvium deposition occurred from 1948 to 1963, the general channel configuration remained the same. A cross section further downstream near Chickasha, Okla., shows no channel change from 1939 to 1963.

In the downstream segment of the Washita River basin, large flood flows in the 1940's and 1950's also damaged the channel system, but on a

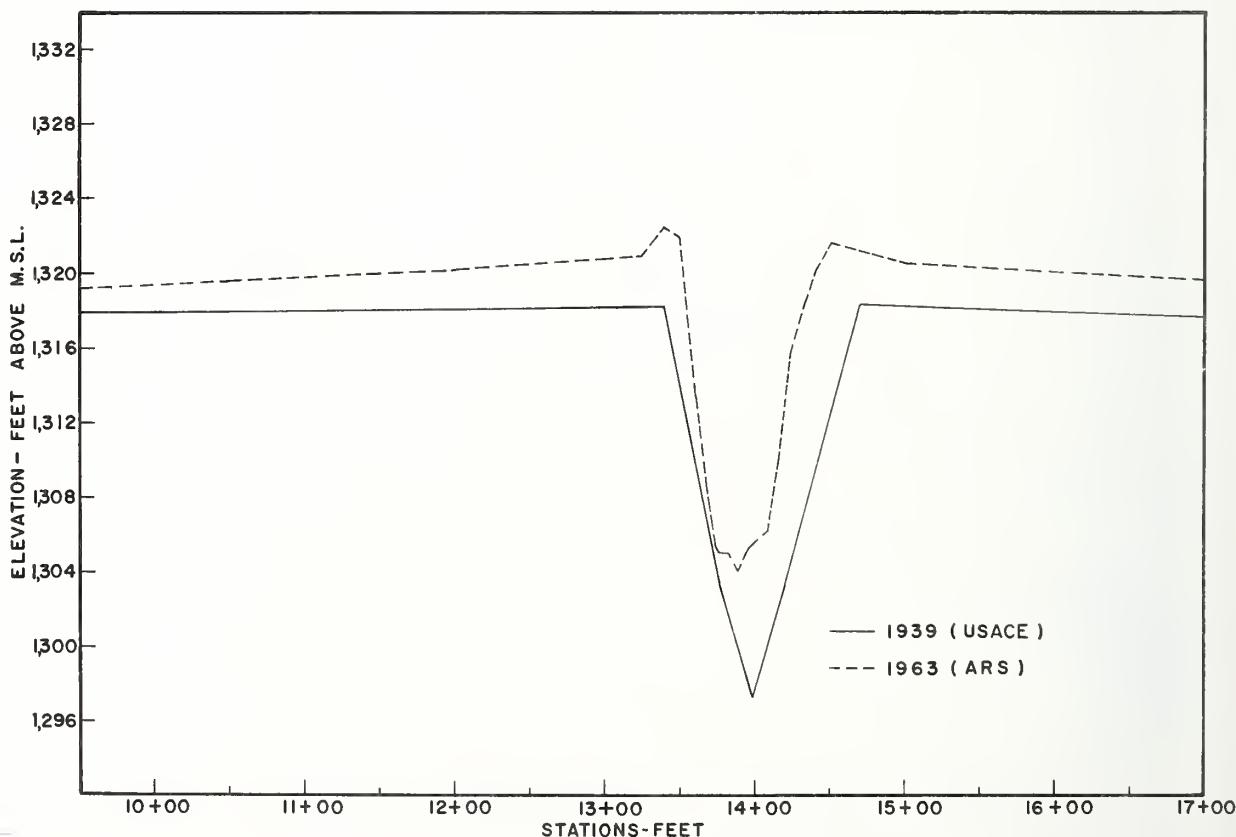


FIGURE 11-3.—Cross section FH2 on Washita River near Mountain View, Okla. USACE, U.S. Army Corps of Engineers.

larger scale. Much of the channel nearly doubled in width, and some reaches had up to 12 feet of channel deposits at times (fig. 11-4). Accelerated meandering and channel straightening, partially man-induced, occurred. To alleviate channel bank erosion, land owners cut through many meander loops, which shortened some channel reaches by 40 percent. The migrating channel left behind sandy, unproductive, low-lying land that supports saltcedar on the streambank and cottonwood saplings elsewhere.

Notes of an original county survey in 1898 offer insight into channel shapes. Although the channel width measurements apparently were made along section lines (and therefore indicate extra width where the channel was not 90 degrees to the section line), an approximate width was obtained by surveying the notes for many channel crossings and averaging the lower widths. For Grady and Garvin Counties in Oklahoma, these top widths were about 1.7 to 2.0 chains (112 to 132 feet). Reported channel depths were about 20 feet. Therefore, the 1898 channel was about the

same size or possibly smaller than the channel documented by the U.S. Army Corps of Engineers in 1939.

Meandering on the Washita River was studied by preparing overlay maps from the original county survey data and available photographs. Meander paths for the Anadarko-to-Alex reach were compiled for 1898, 1937, 1948, 1955, and 1961 (fig. 11-5). Meander paths for the other parts of the reach in Oklahoma from Clinton to Dougherty (fig. 11-1) were compiled for only 1937 and 1961 (fig. 11-6). In original county surveys, the Washita River channel appears to have been accurately located in the 1873 survey west of Chickasha but inaccurately located in the 1898 survey east of Chickasha.

The channel data show that little change occurred in the stream's meander pattern and size from the earliest records until the 1939 survey. In the next few years, however, much of the channel doubled in width and shortened up to 40 percent in some reaches. Cross sections surveyed in the

(Continued on page 128.)

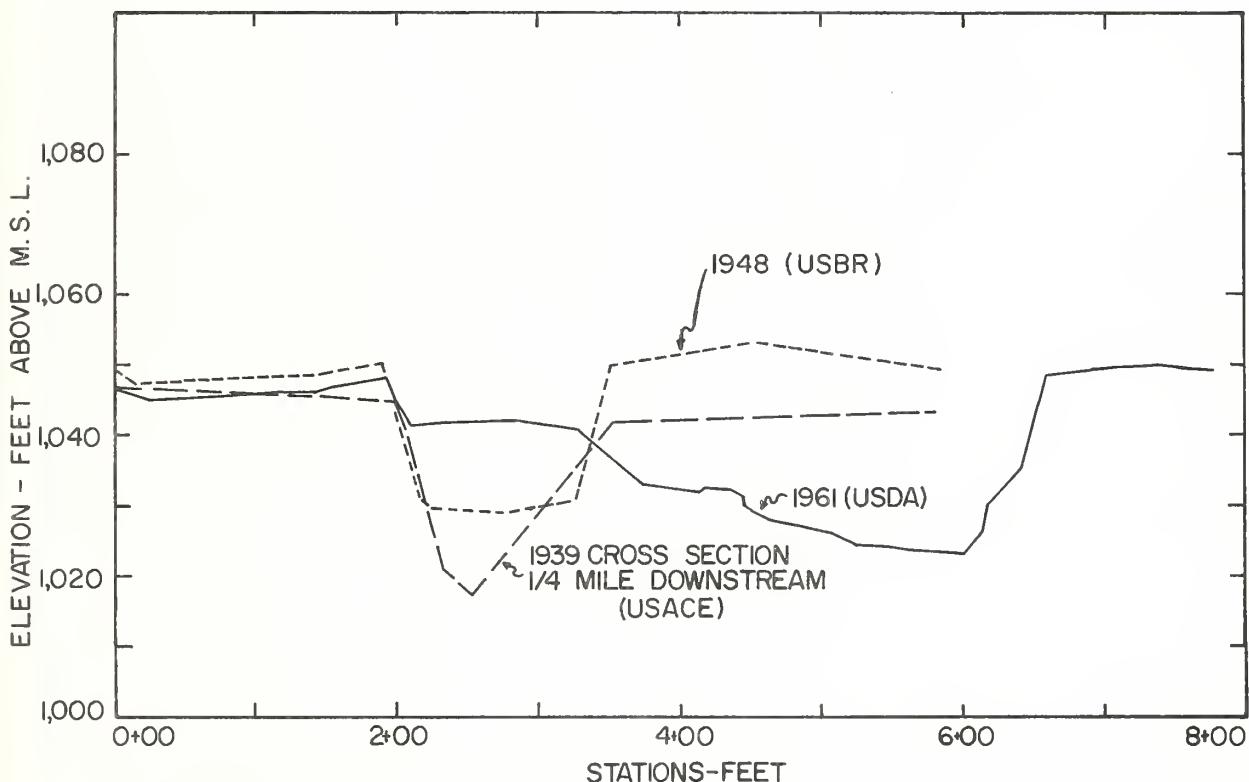


FIGURE 11-4.—Cross section 32 on Washita River downstream from mouth of Little Washita River. USACE, U.S. Army Corps of Engineers. USBR, U.S. Bureau of Reclamation.

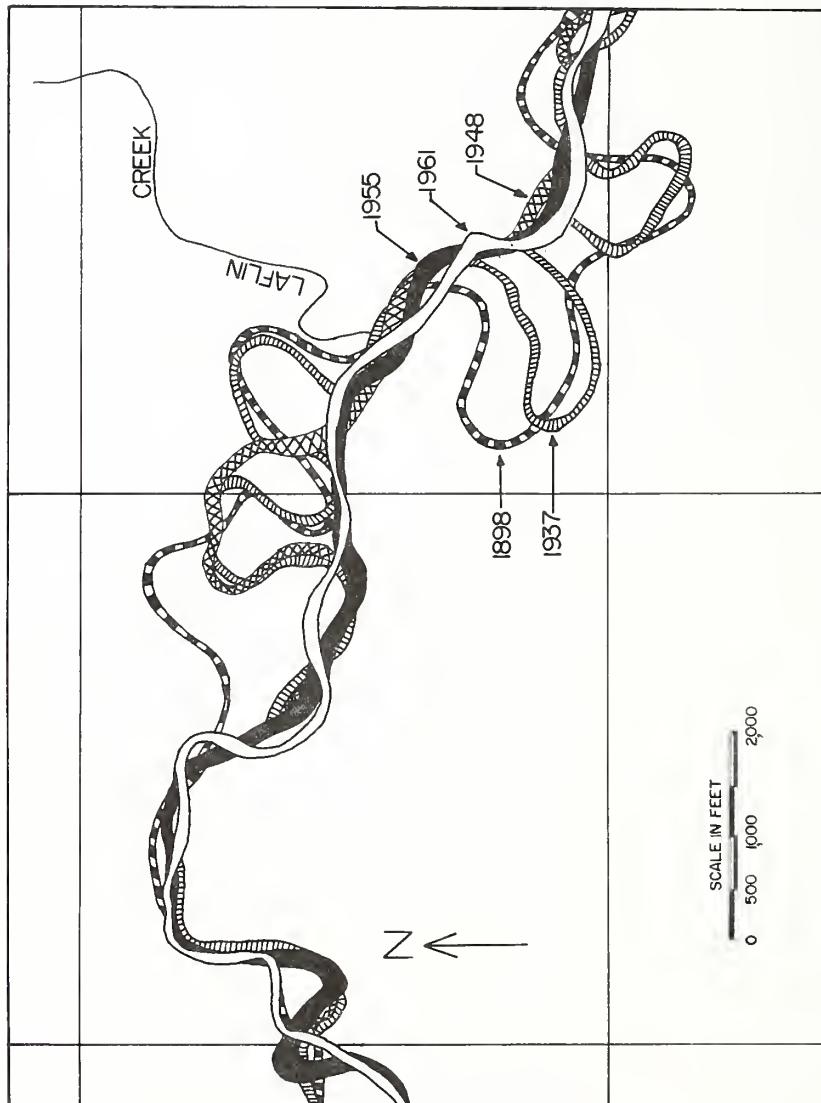


FIGURE 11-5.—Meander patterns for Anadarko-to-Alex reach for 1898, 1937, 1948, 1955, and 1961.

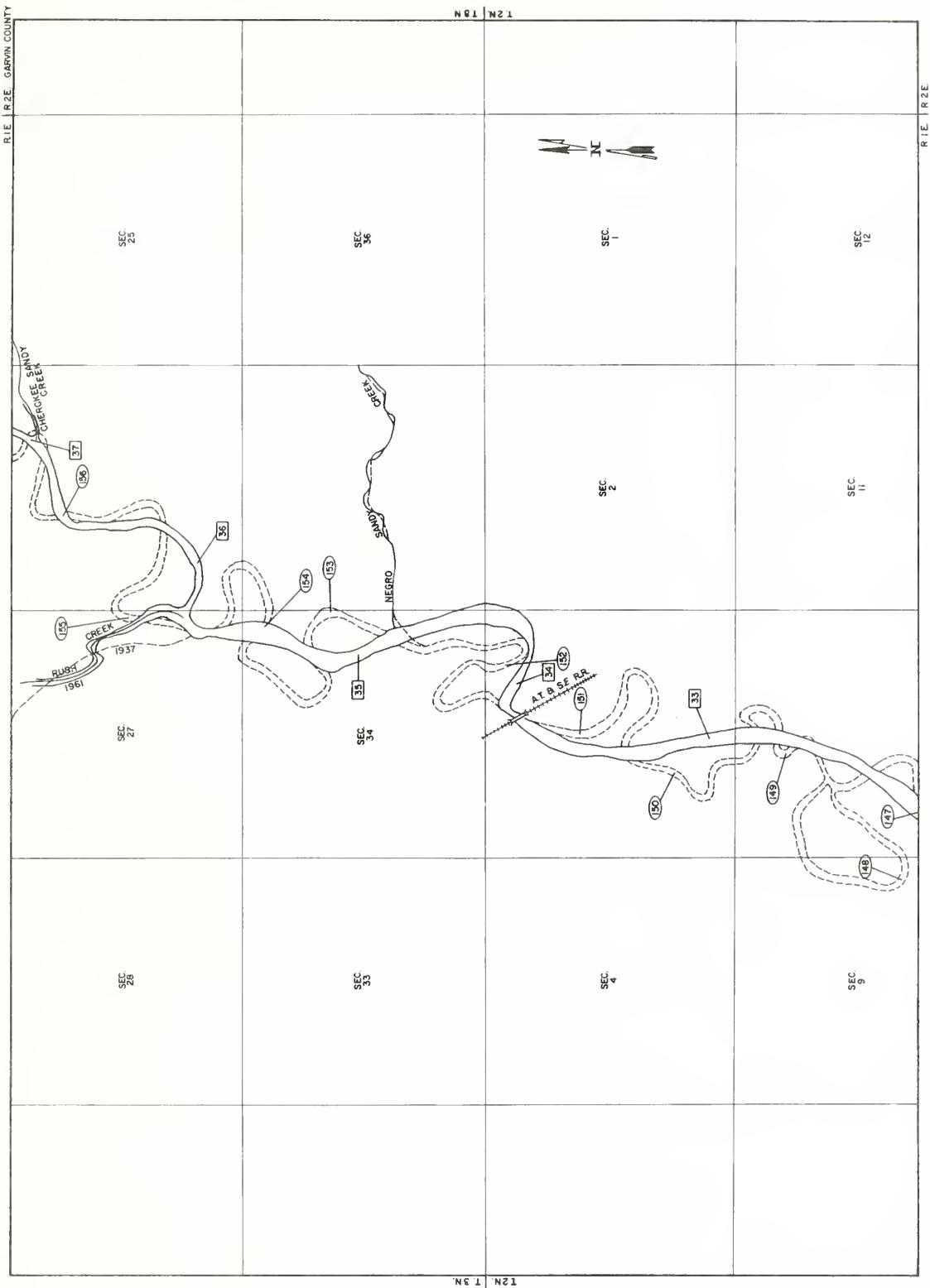


FIGURE 11-6.—Meander patterns for Washita River from 1937 (dashed lines) to 1961. Numbers in ellipses are river miles from mouth in 1939, and numbers in rectangles are river miles from Arbuckle Mountains in 1961.

midsixties show reversal trends; channel banks were rebuilding slowly, becoming more stable, and increasing in sinuosity.

CORING OF RELICT CHANNELS

To gain further knowledge about the Washita River channel, two relict channels, one cutoff and one oxbow, were cored with a Bull soil sampler equipped with 30 feet of steel extensions. Identification of the channel periphery at isolation was made from the color and textural differences of deposits. Postisolation deposits were generally darker and finer textured than the original channel material. A relict channel (a manmade cutoff in 1913) of the Washita River at Pauls Valley, Okla. (fig. 11-1), was very similar in shape to channel cross sections surveyed in 1939 in the same vicinity. The relict channel was deeply incised and slightly narrower than the 1939 chan-

nel. The slope in 1913 of 1.8 feet per mile was similar to that of the 1939 survey, indicating that the meander patterns for the two periods were the same or similar. The lack of fine-medium sands in the bed cores and the V-shape of the channel bed suggested that the Pauls Valley channel of 1913 was stable, had far less sand in transport than today, was swept clean to a bed of pebbles and rocks, and carried almost all material in suspension rather than as bedload.

An oxbow on the flood plain of the Washita River near Chickasha was also cored and found to be somewhat larger in cross section and higher in bed elevation than the 1939 or present channels. The age of this oxbow can only be approximated. It existed before the original county survey in 1898 but is considerably younger than a buried soil profile in the next oldest terrace formation, being radiocarbon dated at 1,000 years before present (Goss et al. 1972). A dating for the oxbow of 7,000 years before present, determined by pollen analysis, appears erroneous.

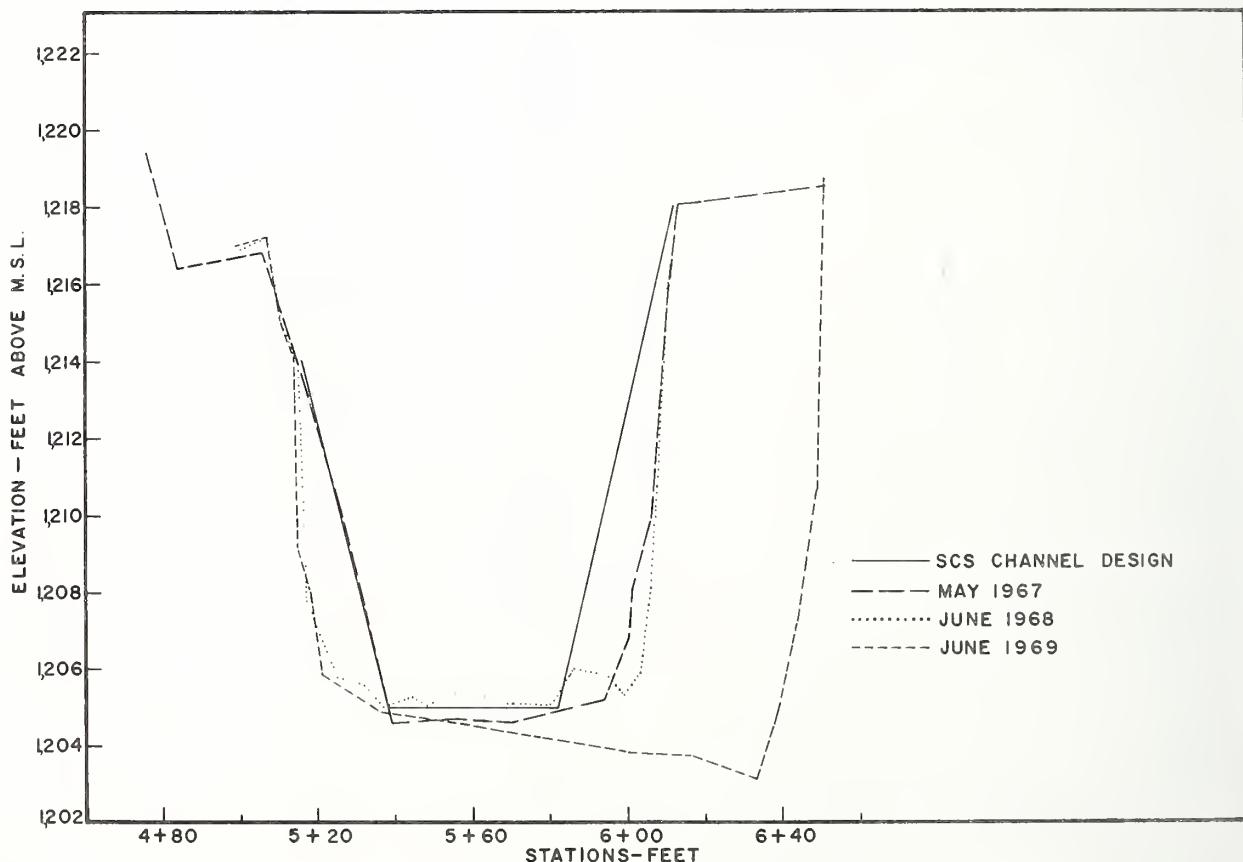


FIGURE 11-7.—Cross sections of dredged Sugar Creek channel near Gracemont, Okla., from May 1967 to June 1969.

RELATIONSHIP OF CHANNEL SHAPE TO COARSENESS OF SEDIMENT LOAD

In the Southern Great Plains research watersheds, the cross-sectional shape of channels was determined to be related to the texture of the suspended sediment load. More specifically, the width-depth ratio (w/d) was related to the percentage of sand (S_a) in the suspended load. For 10 channels the regression equation was $w/d = 0.17S_a + 3.55$, and the statistical r value was 0.90. The channels at two gaging sites were not used in the analysis because they were not in regime. According to cross-sectional resurveys, the channel at the Washita River gaging site at Alex was rebuilding, a change resulting from decreasing sand loads after the accelerated upland and channel erosion of the 1940's and 1950's. The Delaware Creek channel was also excluded. Here the reverse was occurring; a wave of sand was moving down the basin and approaching the gaging site, filling channels and splaying sand onto the flood plain. Although the load was becoming coarser at the gaging site, the channel had not adjusted to the new regime. The above relationship is useful in designing channels and predicting changes from those watershed-treatment measures known to affect the texture of the load.

CORRELATION OF CHANNEL SHAPE TO VEGETATION

A short study was made of channel and floodplain woody vegetation to see if plant species (size and density) affected channel size or shape. Such information was needed to properly interpret the effects of watershed treatment on channels, since channel vegetation was an uncontrolled variable and could change with time. A reach of the Washita River in Oklahoma from Carnegie to Chickasha (fig. 11-1), that had not experienced excessive channel-bank erosion and migration, was chosen for the study. Simple and multiple regression analyses indicated very poor correlation of channel shape variables to vegetation variables. However, trees obviously affected the rate of meandering, though these effects were not researched in the study. Therefore, trees are

very beneficial and desirable for the stability of most stream channels.

CHANNEL BEHAVIOR ON SUGAR CREEK

The Sugar Creek watershed (fig. 12-5) provided a unique opportunity to study erosion and deposition regimes. The high erodibility of the soils, recent large flood flows, and channel dredging have obviously produced massive erosional and depositional changes. The geologic formations, upland soils, colluvium, channel bed and banks, and stream-channel suspended-sediment loads are dominated by a very fine sand with a noticeable lack of clay-size material. This situation creates erosion problems throughout the watershed, and for stream channels, large and small, represents the ultimate in channel instability. Massive geomorphic changes have taken place in short periods of time.

In 1961, localized channel degrading and widening was in progress upstream near Lookeba, Okla., which was probably triggered by straightening of the downstream channel a few years before. Downstream near Gracemont, Okla., considerable flood-plain deposition was taking place. The channel was sanded-in, and flows of over 1,000 cubic feet per second spilled over the banks, causing sizable overbank accretion and backswamps.

Aerial photos taken in 1955 in this area show a long, old channel, roughly parallel to the present Sugar Creek channel, that had probably been abandoned by water flow when the channel bed became higher than the adjacent flood plain. A few miles farther downstream, the channel had virtually disappeared. Thus, most of the remaining sediment load had apparently been deposited, leaving little sediment to reach the Washita River. The last half mile of the Sugar Creek channel near the Washita River was small, V-shaped, and very sinuous, indicating a stream that had carried less flow than upstream channels and that had transported little or no sand. In 1965, the second largest flow of record scoured the flood plain at some places and caused large sediment deposits at other places. The channel upstream from Binger, Okla., was flushed of sediment and deepened, exposing pilings from early bridges.

Channel dredging was part of the flood-control

plan for the Sugar Creek watershed. Channel erosion after dredging caused considerable deposition in the Washita River. Figure 11-7 shows a cross section of Sugar Creek about 10 miles above its mouth. From construction in early 1967 to June 1969, the size of the channel almost doubled. Some of this eroded material was deposited near the mouth of Sugar Creek, as shown in figure 11-8; thus, redredging was required in June 1967. By June 1969, the mouth had again filled with eroded material, but sizable sustained base flows after 1969 eroded this deposit. The profile in figure 11-9 shows that much of the eroded material from the Sugar Creek channel was deposited in the Washita River. By 1969, maximum deposition depths were 6 feet, and the deposited volume was 650 acre-feet. Surveys in 1973 showed that much of the deposit had been transported downstream and that the new bed was parallel to and approximately 2 feet higher than the bed of 1966. The huge sand loads that

entered the Washita River not only caused aggradation but also increased bank erosion. Although the exact erosion mechanism is not understood, this lends support to earlier observations linking heavy sand loads to instability.

The new Sugar Creek channel widened about 4 miles above the confluence with the Washita River, but cross-sectional resurveys showed that the bed neither scoured nor filled. This portion of the channel appeared to be in regime, and the measured slope was 0.0010 foot per foot or 16 percent flatter than the design slope of 0.0012 foot per foot. An attempt was made to check the tractive-force and regime procedures of channel design. However, there was no existing method for computing a weighted or effective hydraulic radius or discharge from the mix of flows occurring in nature. The maximum flow could not be used because the tractive force was 0.68 or 8.5 times greater than the recommended tractive force. If the width and slope of channels carrying

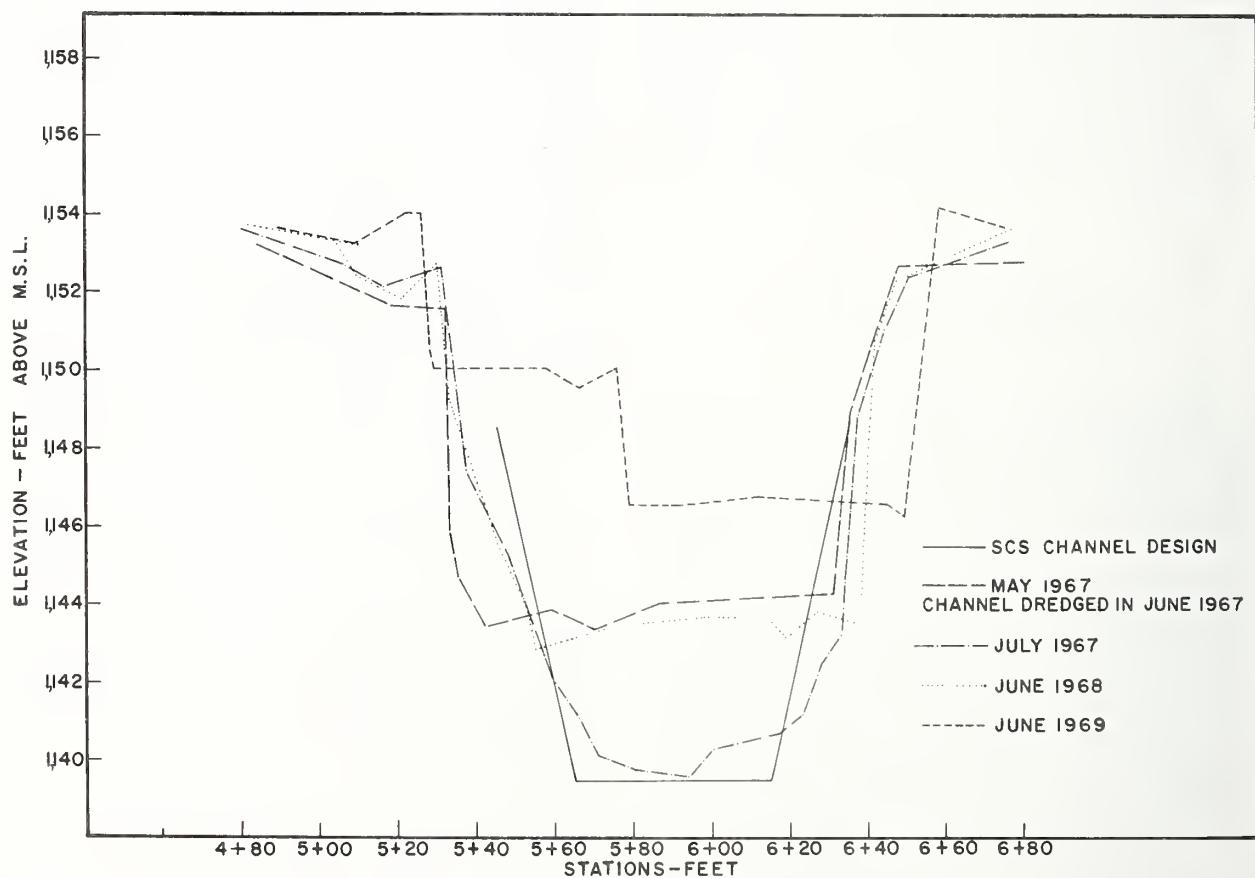


FIGURE 11-8.—Cross sections of dredged Sugar Creek channel near confluence with Washita River from May 1967 to June 1969.

heavy sediment loads are designed for maximum flows, these channels will silt-up from the deposition of smaller flows; therefore, there is need for more research.

BANK-PROTECTION MEASURES

Numerous types of bank-protection devices have been installed on the Washita River and its tributaries since the mid-1940's by various Federal, State, and county governments; oil companies; and farmers. Those protection measures and brief descriptions of their effectiveness are given below.

<i>Device</i>	<i>Performance</i>
Kellner jacks	Good and lasting protection when

Riprap	properly installed.
Timber-pile jetties	Good and lasting protection if adequate in size and amount.
Old auto tires banded together.	Poor; planking requires occasional repair and flows pass through and under jetties, permitting erosion to continue.
Car bodies	Poor; all installations have failed partially or completely; may have use in combination with other protection, such as on the upper bank where there is less flow stress and with riprap on the lower bank.
Trees:	Very good if placed in sufficient numbers and properly anchored.
Plantings	Poor.
Natural growth	Mediocre.
Large felled trees, inverted.	Good.
Single fencing	Adequate on tributaries.

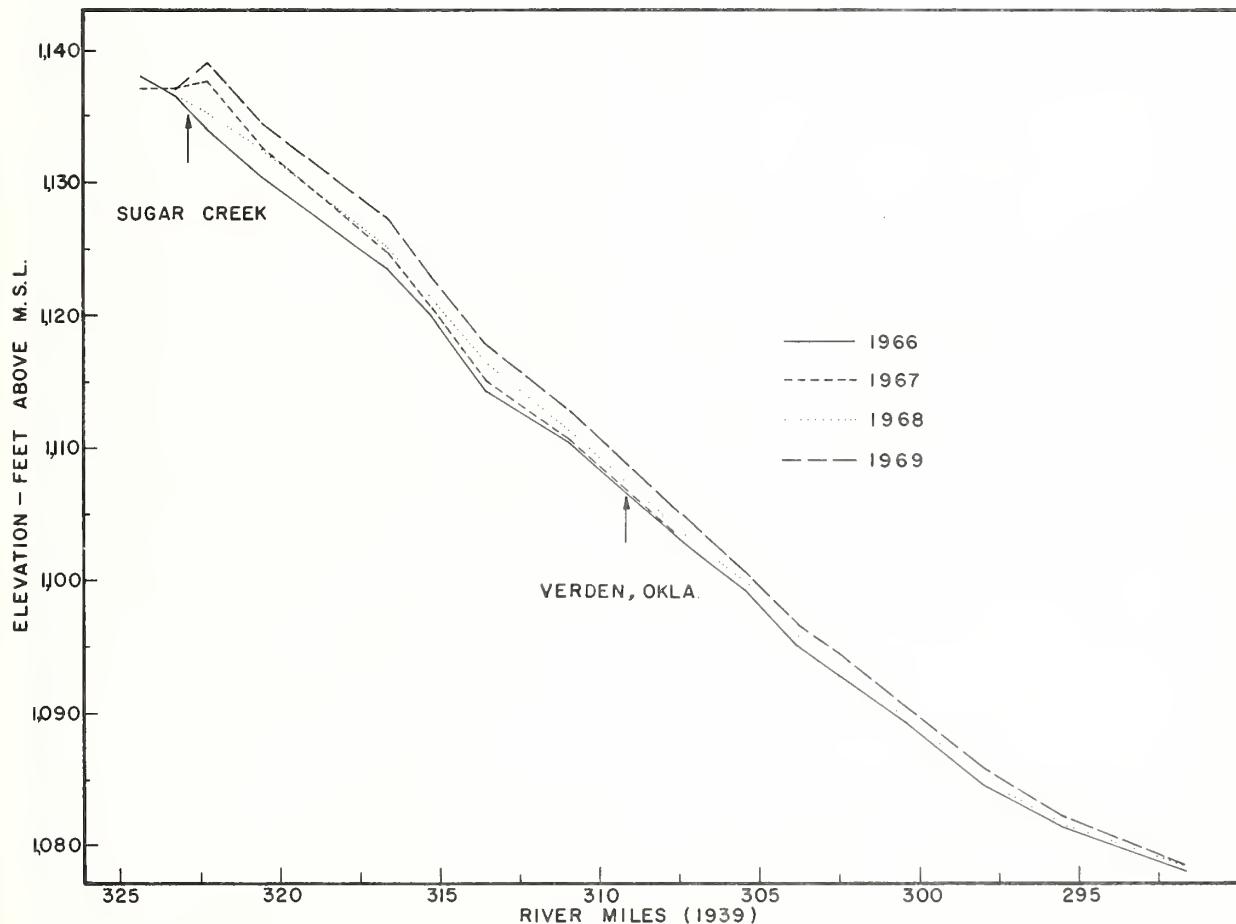


FIGURE 11-9.—Profile of Washita River bed below dredged Sugar Creek channel.

EFFECT OF FLOODWATER-RETARDING STRUCTURES ON CHANNELS

The effect of these structures on channels is not yet clear because the period of observation has been short. Final channel adjustments to upstream-flow and sediment changes may require 50 years. Channel changes caused by natural climatic shifts and variations may overshadow manmade changes. A further complication is that the uplands were treated toward the end of a major channel-adjustment period on the Washita River.

It appears, however, that small channels immediately below floodwater-retarding structures tend to aggrade, which is just the opposite effect of large structures. Aggradation occurs because peak flows are greatly reduced, causing an even greater reduction in the sediment-transporting capacity. (Transport is proportional to the discharge approximately squared.) The sediment supply comes from the dam's downstream face and the local streamlets. Deposition is further encouraged by the vegetation that springs up and flourishes on the banks and bed with the prolonged base flow of new-flow and ground-water regimes.

Some major box-shaped tributary channels that were eroding before the structures were installed are now smaller, V-shaped, stable, and tree-lined (Schoof et al. 1980). The rampant bank erosion on Winter Creek stopped abruptly after floodwater-retarding structures were installed. Decreased channel erosion accounted for much of the 60-percent sediment-yield reduction that occurred with treatment (Allen and Welch 1971). Deductive reasoning suggests that major channels will in time decrease in size because the structures decrease peak flows. If sediment loads decrease, the channels should degrade and become more V-shaped, especially if the major decrease is in the coarse part of the load.

SUMMARY

To properly assess the effect of any basin treatment on a channel system, the historical behavior of the channel must be known and also whether any morphological change or cycle is underway, and if so, where the system is in the change or cycle. The earliest historical records (1898 to 1939) of the behavior of the Washita River show that

little change had occurred in the Washita River channel downstream from the Little Washita River confluence. Then in a relatively short 20-year period, a massive erosional change took place. The channel approximately doubled in width, and a channel meander realinement occurred. Some reaches shortened by 40 percent. Large flood flows and sediment loads in the 1940's and 1950's apparently instigated the erosional cycle. Presumably, the percentage of sand in the sediment load increased, causing a wider channel. In this area, relating the width-depth ratio of channels to the percentage of sand in the suspended sediment load gave a fairly good correlation. The percentage of sand delivered to a channel system appears to increase with the size of runoff events, the amount of cultivated land, and the amount of gullyling.

The Sugar Creek watershed, with its fine sandy erodible soils, the extra large flood in 1965, and the channelization project, presented an opportunity to observe massive erosional and depositional changes that occurred in a very short period of time. Before channelization, flows in the midreach near Gracemont often spilled out of the small sanded-in channel and created overbank deposits near the channel and backswamps farther away. Only a minor part of the sediment load appeared to reach the Washita River. The large flood in 1965 flushed the channel upstream from Gracemont and exposed buried bridge piers from earlier times.

After the channel was dredged, large flows about doubled the size of the channel cross section. Much of this erosion was deposited in the Washita River, where slopes and velocities decreased. In a 10-year period, however, much of this deposit had been scoured out.

One midreach of the Sugar Creek channel appeared to reach a regime condition a few years after dredging. The slope was measured and found to be 0.0010 foot per foot or 16 percent flatter than the design slope. An attempt was made to check the tractive-force and regime procedures for channel design, but this was unsuccessful because no procedure existed for obtaining an effective or weighted hydraulic radius or discharge for the mix of flows occurring in nature.

A survey of bank-protection devices was made on the Washita River. Kellner jacks, riprap, car bodies, and felled inverted trees offered good protection, but timber-pile jetties, old auto tires, and tree plantings were generally inadequate.

The effect of floodwater-retarding structures on the Washita River channel is unclear because of the short observation period. However, with time (possibly 50 years) the channel should degrade slightly and become more V-shaped.

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Section 12.—Ground-Water Movement and Quality

INTRODUCTION

Ground-water studies were commenced in southwestern Oklahoma in 1961 on the Washita River basin in the reach between Anadarko and Alex. The studies were designed to provide needed research as expressed in "Soil and Water Conservation Research Needs" (U.S. Soil Conservation Service 1960). The specific subjects addressed were effects of watershed-protection programs on ground-water accretion and movement, ground-water contributions to streamflow, effects of impervious channel structures on restoration of valley water-table levels, and recharge of aquifers and dug ponds.

The physical boundaries and geologic and hydrogeologic data gathered to describe the aquifer system within the study reach are presented in section 2 of this report. Because much of the watershed-treatment program authorized by Public Law 566 was commenced or completed before the needed geologic studies were completed, it became necessary to use mathematical modeling techniques to quantify ground-water movement and storage within the aquifer system.

The bedrock and alluvium in much of the study reach contains evaporite mineral deposits. Ground-water quality, as it was impacted by the watershed-treatment program and by naturally occurring salt deposits, was monitored and related to ground-water occurrence and movement to the greatest possible extent, although this subject is not specifically mentioned above.

GROUND-WATER LEVELS

The general west to east gradient of the water table within the Washita study reach is shown in figure 12-1. An elevation differential of nearly

500 feet exists between the highest point on the water table in the northwest portion of the study area and the lowest point, which is at the Alex gaging station on the eastern boundary of the area. The ground-water conditions along the Washita River and its tributaries are effluent (gaining streams) except for brief periods of storm flow. The base flow is derived from the percolation of precipitation that falls directly onto the surface of the study reach.

The depth to the water table is about 20 feet in the alluvium and 60 to 90 feet in the bedrock. Annual fluctuation in water levels caused by seasonal and climatological conditions are as much as 13 feet in the flood plain southeast of Anadarko. Channel modification on the part of Tonkawa Creek has lowered and stabilized water levels in that area.

GROUND-WATER QUALITY

The dry summer months following rainy springs allow naturally occurring salts, derived from near-surface ground water, to accumulate in the flood-plain deposits. Saline areas (fig. 12-2) occur in regions where the alluvium contains gypsum, halite, or epsomite that have concentrated as a result of cyclic wetting and drying of the sediments. These cycles bring mineral-laden waters nearly to the surface of the soils, which upon drying tend to deposit salts over areas of shallow water tables.

Yost (Yost and Naney 1975) reported that naturally occurring saline soil problems are most common in those valley areas of the Washita River basin where the ground water is both highly mineralized and shallow enough to be subject to evapotranspiration. This combination of salinity and high water table is common in

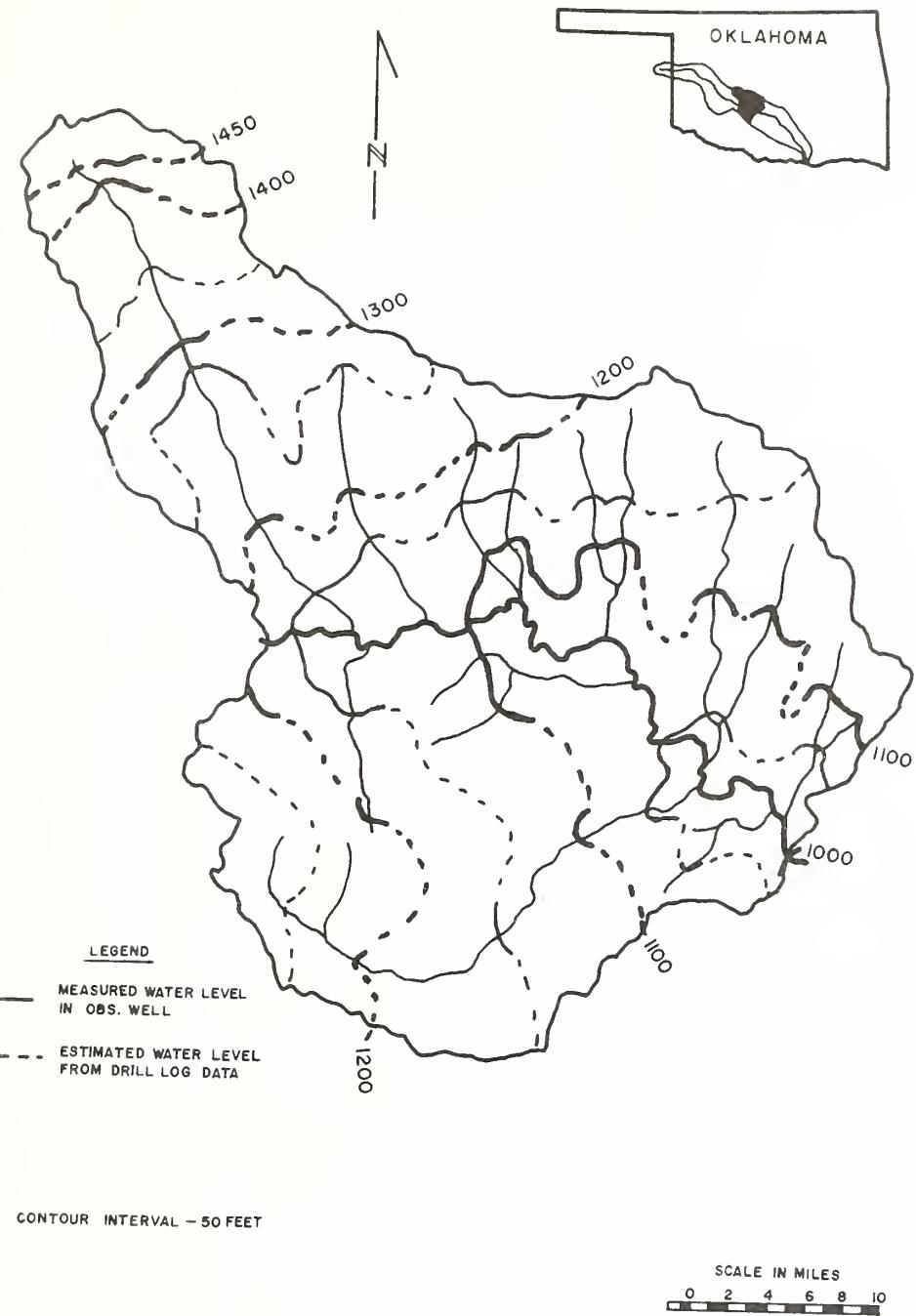


FIGURE 12-1.—Ground-water elevations (feet above m.s.l.) within the Washita study reach.

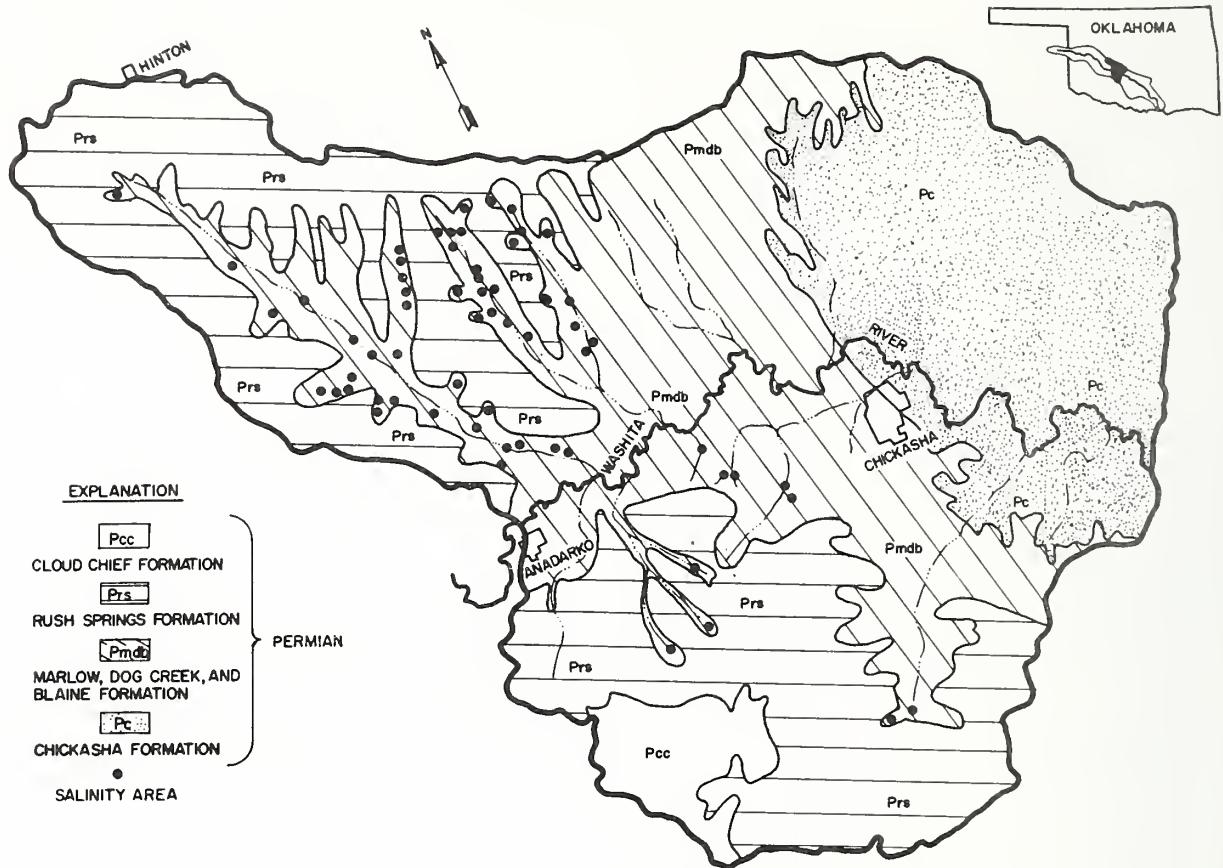


FIGURE 12-2.—Distribution of saline areas in relation to geological formations.

valleys where erosion through the Rush Springs sandstone into the highly mineralized zones of the Marlow formation has occurred and where the Dog Creek shale or Blaine formation, also of Permian age, are in contact with Quaternary age alluvium. Small valley gradients and associated poor drainage, combined with plentiful recharge water from the Rush Springs sandstone and the alluvium, produce the shallow water tables. The shales supply the soluble minerals. Thus, in these particular valley areas, conditions are ideal for increasing the concentration of minerals in the water and soil, both by the addition of minerals to the solution and by the subtraction of water from the solution.

The saline soil areas were identified by the presence of a visible veneer of white salts on the ground surface and by an associated scarcity of vegetation. The affected areas were generally elongated, 1 to 100 acres in size, and scattered along the valleys where the best farm land normally occurs.

Increases in soil and water salinity are also found downstream from floodwater-retarding structures as a result of seepage from the reservoirs. The leaching action and near-surface evapotranspiration concentrate salts in the flood plain directly downstream from the dams. Yost (Yost and Naney 1975) identified the types of problems associated with seepage past a dam. These problems are illustrated in figure 12-3.

Seepage from reservoirs can cause or aggravate one or more of the following interrelated conditions that limit the usefulness of land and water resources: (1) loss of water from reservoir storage, (2) damage to the structure, (3) rise of water table and waterlogging of soil, (4) mineralization of ground water and surface water, (5) loss of water resources by evaporation and transpiration, (6) development of saline soils, (7) invasion of land by undesirable phreatophytes—plants that habitually obtain their water supply from the zone of saturation, and (8) poor drainage caused by clog-

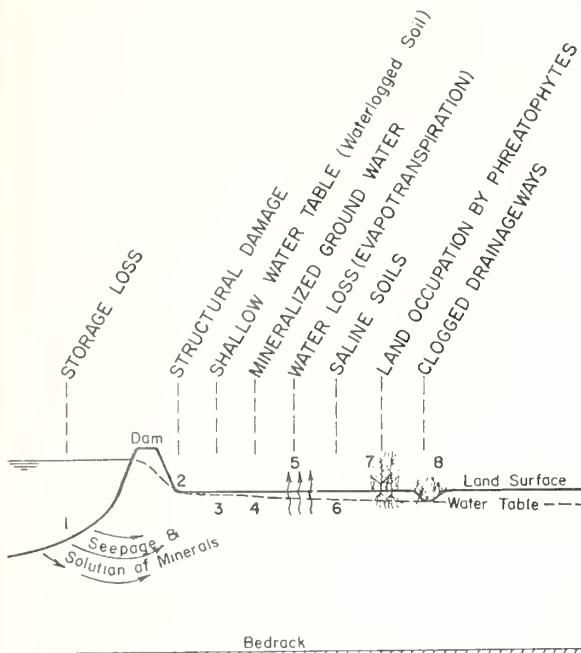


FIGURE 12-3.—Problems associated with seepage from reservoirs.

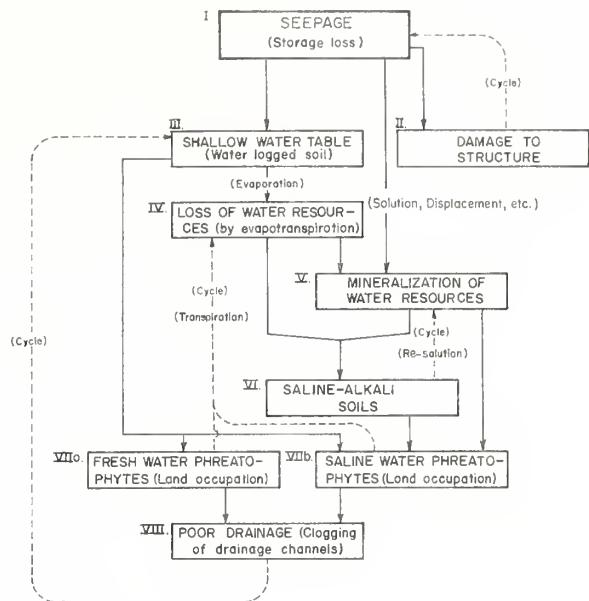


FIGURE 12-4.—Interrelations of land- and water-use problems associated with seepage from reservoirs.

Table 12-1.—Total water hardness, expressed as mg/l of CaCO₃, above and below selected dams on Sugar Creek watershed in 1963 and 1964¹

Geologic formation	Dam site ²	Lake water		Seepage water				Springs below dam	
		³ 1963	⁴ 1964	Left toe drain		Right toe drain		1963	1964
				1963	1964	1963	1964		
Rush Springs	16	140	150	.....	.....	560	.....	530	550
	19	260	170	.....	.....	390	400	.....	.....
	11	120	190	.....	.....	440	560	370	.....
Marlow ⁶	20	410	340	1,500	1,740	840	700	.....	.....
	9	220	230	1,440	1,400	1,110	1,130	.....	.....
	24	220	470	1,470	1,390	1,370	.....	.....	.....

¹Blank indicates that no sample was available.

²Dams constructed before October 1963 in the Rush Springs sandstone and Marlow formation.

³Samples were taken Oct. 9 or 21, 1963 or Nov. 1, 1963, after dam construction.

⁴Samples were taken Oct. 14, 16, or 20, 1964, after dam construction.

⁵Mixed with plunge basin water.

⁶Gypsiferous.



FIGURE 12-5.—Locations of reservoirs sampled in water-quality study.

ging of drainage channels by plants and sediment.

Depending on the local environment, any of these conditions, except storage loss and damage to the structure, can also develop naturally in valley areas that do not contain dams. The type and magnitude of problems that may result from dam construction depend on such local environmental factors as geology, soil, hydrology, geochemistry, meteorology, and biology.

The interrelation of seepage and other problems is shown in figure 12-4. Loss of stored water via seepage can lead to structural damage (increased permeability, piping, slumping, etc.), which in turn may increase the seepage rate. Seepage may also cause a shallow water table, which, when

subjected to evaporation, successively results in loss of water, mineralization of water resources, and salination of soils. A shallow water table also is conducive to the growth of phreatophytes. Depending on the mineral concentration of the water and soil, these plants will either be freshwater or saline types, both of which may wastefully use land and water resources. Salt-cedar (*Tamarix*), a fast-growing, saline-type phreatophyte, is particularly troublesome in the shallow water-table areas that occur where seepage is active.

Studies of water quality above and below six floodwater-retarding structures on the Sugar Creek watershed in 1963 and 1964 showed increased mineralization of seepage water below the

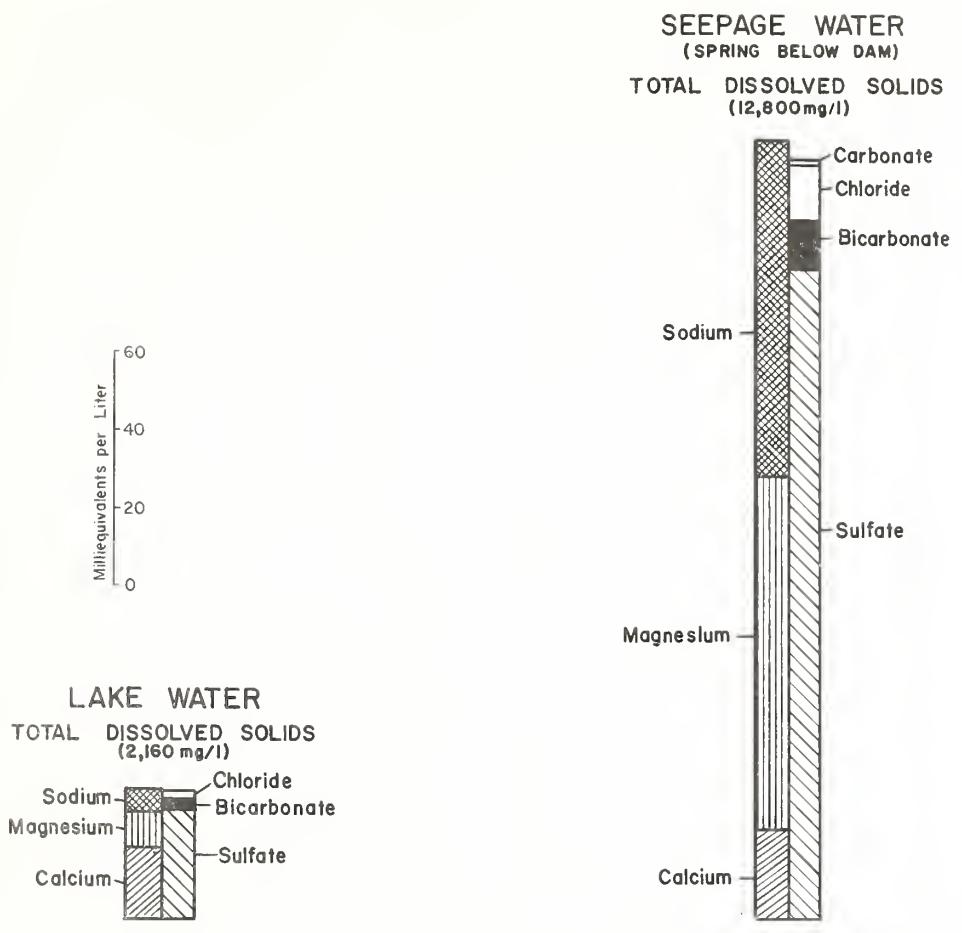


FIGURE 12-6.—Effects of seepage from Lake Chickasha on downstream water quality.

dam, as much as 4.7 times that of water sampled above the dam. Data from these studies are summarized in table 12-1. Figure 12-5 shows the locations of the reservoirs sampled in this study as well as Lake Chickasha, a water-supply lake for the city of Chickasha, Okla. Pionke (Pionke and Workman 1974) found seepage to be a dominant cause of salt load loss from structures in the Sandstone Creek watershed, a tributary of the Washita River in western Oklahoma.

The effects of seepage from Lake Chickasha, described by Yost (Yost and Naney 1974), on downstream water quality are shown in figure 12-6. Comparisons of these chemical data show that the concentrations of both total dissolved solids and individual chemical constituents increased appreciably from the upstream to the downstream side of the dam. Total dissolved solids increased from 2,160 to 12,800 milligrams per liter across the dam, an increase of 10,640

milligrams per liter or a relative increase of 5.93 times. Total hardness increased from 1,360 milligrams per liter in the reservoir to 5,650 milligrams per liter in the seepage spring, an increase of 4,290 milligrams per liter or 4.16 times.

All of the measured chemical constituents increased, but generally not in proportion to each other or to the total dissolved solids. Magnesium content increased 9.8 times compared to an increase in calcium content of only 1.1 times, which was the smallest increase among all constituents. Calculations based on the solubility of gypsum, reported to be 2.2 grams per liter (Hodgman et al. 1959), showed the solution concentration of calcium in the seep to be controlled by the solubility of gypsum. Sodium content increased 15.5 times, which was the largest increase among all constituents. Bicarbonate increased 5.4 times, sulfate 5.9 times, and chloride 6.8 times. Because of these disproportionate changes, the general chemical

character of the water changed from one of calcium magnesium sulfate in the reservoir to one of magnesium sodium sulfate in the seep. Increases in total dissolved solids of nearly sixfold, as well as increases in most of the chemical constituents, indicate that the salinity buildup downstream from earthen dams may cause deterioration of both soil and water quality and limit the usefulness of land and water resources immediately downstream from such structures. The effects are generally limited to a distance less than 600 feet downstream from the structure and impact about 15 acres of flood-plain land at each site.

This increase in salinity during seepage affects water quality in downstream areas. Therefore, in areas where the salinity of surface or ground water is marginal for either present or proposed water uses or where a significant salinity potential exists because of a preponderance of saline and highly permeable geologic deposits in the area, some alternatives for limiting this mechanism of salinization should be considered. These alternatives would include reducing the permeability of the dam and foundation; locating the dam site in less-permeable, less-saline geologic terrain; or diluting and reducing the saline seepage by designing the dam to increase surface-water outflow at the expense of storage capacity.

Since these studies were conducted, the reduction or elimination of these problems was accomplished by design changes adopted by the Soil Conservation Service (SCS) that increased the utility of the limited land and water resources in the Southern Great Plains. These changes included the use of multiport principal spillways to reduce hydraulic head differences across seepage-prone structures and the use of tile drains downstream from structures where seepage was identified as a potential problem.

MODEL STUDIES

Three types of ground-water flow problems were modeled using numerical modeling approaches; the results of the completed model studies are summarized below.

A determination of maximum annual yield was made, using a finite difference model, for the Washita River alluvium between Anadarko and Alex (Kent and Naney 1978). The annual yield was based on computer simulation of all known

pumpage and subsequent pumpage allocated over 20 years (July 1, 1973 to July 1, 1993). The maximum annual yield was 97,000 acre-feet per year, proportioned as 2.0 acre-feet per acre per year. The modeling was based on the following parameters: (1) a total land area of 69,760 acres overlying the alluvium in the main reaches of the Washita River, (2) a total of 1,423,000 acre-feet of storage in the basin as of July 1, 1973, (3) an estimated rate of natural recharge of 1.44 inches per year, (4) an average transmissibility of 20,000 gallons per day per foot, and (5) a 30-percent average specific yield of the alluvium. The model adapted for these studies may be useful as a tool for predicting subsurface flow and associated chemical transport in a river basin environment.

Naney et al. (1978) published a model for predicting base flow based upon the theory of flow to parallel drains. The model was calibrated on 3 years of data from watershed 5142 on Spring Creek (fig. 5-3) and was validated by hydrograph comparison for 1971 and 1972. The predicted and actual base-flow hydrographs are shown in figure 12-7 for comparison.

A method for estimating the effects of increased reservoir head on seepage from a floodwater-retarding structure was published by Naney and Thompson' (1979). The method was developed using data from SCS site 13 on the Sugar Creek watershed (fig. 2-1).

SUMMARY

The base flow in the Washita River and its tributaries results from effluent ground-water conditions. Water-table depths are about 20 feet below the surface of the alluvium and as much as 90 feet below outcropping bedrock surfaces near the watershed divide. Annual water-level fluctuations have been as much as 13 feet in some areas of the Washita River flood plain. However, channel modification on Tonkawa Creek has reduced this annual fluctuation and tended to stabilize water levels where near-surface water-table conditions existed previously.

The Permian age red beds in the study area contain evaporite deposits that, as a result of erosion and weathering, have accumulated in the flood-plain alluvium. In some areas, the seasonal fluctuation of the water table has created areas of highly saline soil and water. Floodwater-retarding structures have increased soil and

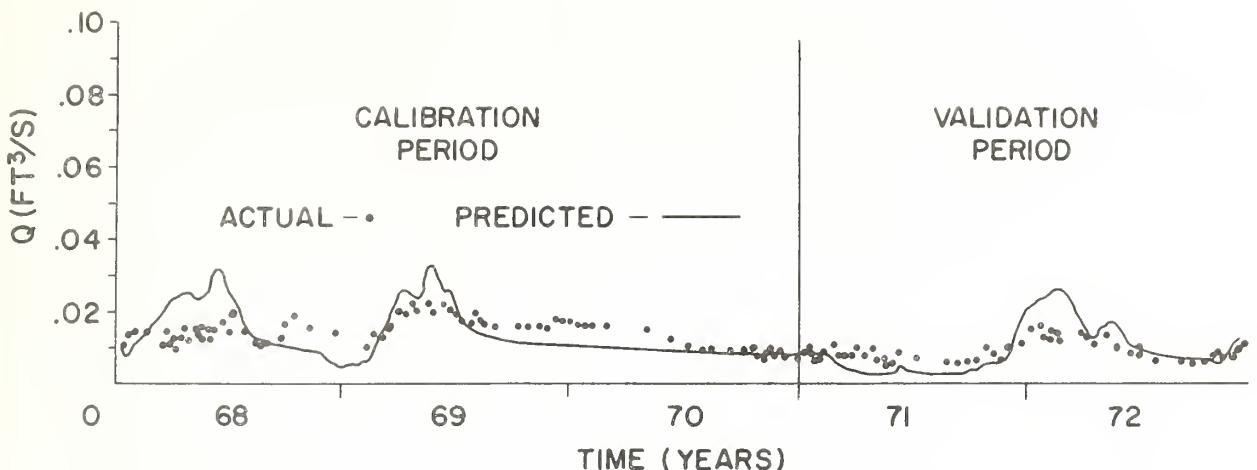


FIGURE 12-7.—Predicted and actual base flow on Spring Creek watershed 5142.

water salinity in some geologic environments. These increases were partially the result of seepage merging downstream from the structures, which has maintained shallow ground-water conditions over a long period of time. In the structures observed, the deterioration of both soil and water quality was limited to less than 1,500 feet downstream from the structure.

Mathematical modeling techniques were applied to a variety of ground-water-related problems within the study area. A maximum annual yield of 97,000 acre-feet per year, proportioned as 2 acre-feet per acre per year, was determined for the unconsolidated sediments of the Washita River alluvium between Anadarko and Alex. Additionally, mathematical models for predicting base flow from a small watershed and for estimating the effects of changes in reservoir head on seepage from a floodwater-retarding structure have been published as a result of these studies.

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Section 13.—Surface-Water Quality

INTRODUCTION

Water-quality research was not a part of the original study objectives in the Southern Great Plains Research Watershed. The first water-quality samples were taken to assess salinity in seeps below earthen dams during low-flow periods. After a few years, additional water-quality samples were taken to assess the salinity of runoff from some of the tributary watersheds.

In 1968, a formal research program was initiated to investigate salinity problems in the Southern Great Plains. The gist of the research was to study the influence of flood-control structures and other upstream management practices on the water quality of the Washita River basin, particularly the salinity levels of the outflow waters. This project was later expanded to include the influence of climate and watershed characteristics on the quality of stream waters.

Because of increased public concern over the quality of the total environment, a water-quality research program was begun in 1972 at the Southern Great Plains Watershed Research Center, Chickasha, Okla., to study the impact of agricultural chemical runoff from rangeland and cropland. After the passage of Public Law 92-500, commonly known as the Clean Waters Act, the research program for assessing the quality and controlling the pollution of receiving waters from agricultural chemical runoff was accelerated. In cooperation with the Agricultural Research Service (ARS) Water Quality Management Laboratory at Durant, Okla., several crop and rangeland watersheds were instrumented for assessment of nutrient runoff. These studies were coupled with the sediment sampling program, which had been in progress for several years.

The following discussions give the details, results, and significant findings of surface-water-quality research conducted at Chickasha. Of course, a portion of this work is continuing, and the data collected are still being analyzed and

used in the mathematical modeling of hydrological transport processes that are relevant to the nonpoint source pollution section (208) of the Clean Waters Act.

SALINITY RESEARCH

As previously stated, this research was initiated in 1968, and field instruments were installed in the fall of that year. Previously, chemical data had been collected by the U.S. Geological Survey (USGS) only at streamflow stations along the main stem of the Washita River basin. These data showed the salt contents in the Chickasha study reach to normally exceed 500 parts per million of total dissolved solids and 250 parts per million of sulfate, the U.S. Health Service's recommended levels at the time for human consumption. These levels at the basin scale were mostly attributable to natural geologic leaching and not to the activities of man. However, water- and land-management practices could have potentially altered or seriously increased stream salinity on a local basis, depending on watershed characteristics and practice intensity. Therefore, the following programmatic objectives were established:

1. Determine the effects of the agricultural flood-control program on the water quality (total and specific dissolved salts) of the Washita River and its tributaries.
 - (a) The effect of water-retention on reservoir water quality (total and specific dissolved salts).
 - (b) The effect of a reservoir on downstream water quality (total and specific dissolved salts).
2. Determine and evaluate the important salt sources that are major contributors to the salinity of the Washita River and its tributaries.
3. Devise practical techniques for the prediction and partial control of salt inflow into the Washita River and its tributaries.

To achieve these objectives, sampling stations were established at existing (stream) gaging sta-

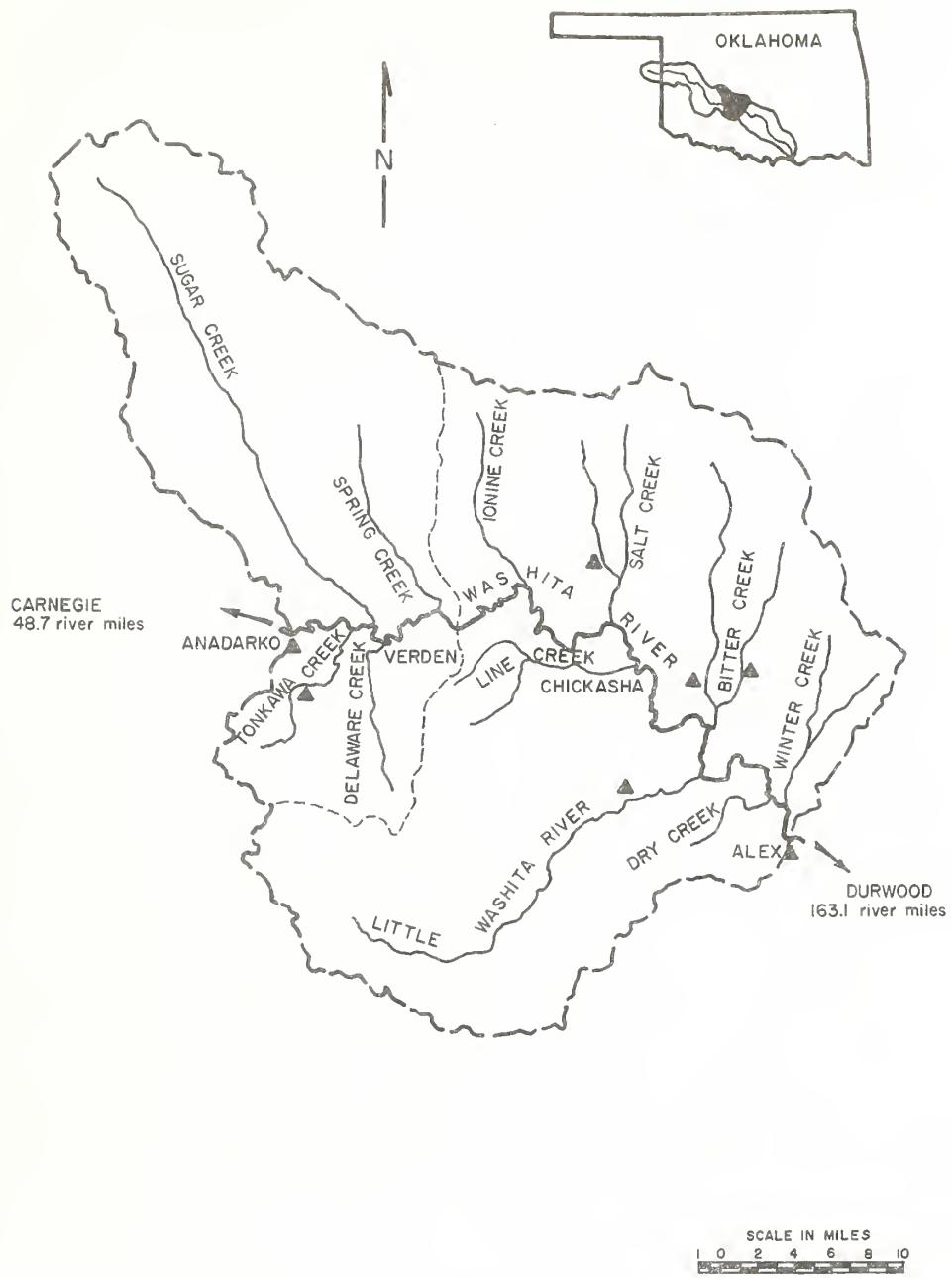


FIGURE 13-1.—Water-quality gaging stations in the study reach of Washita River basin.

tions operated by the Center and at selected flood-control reservoirs and farm ponds. Two stations were established on the main stem network, one at the upper end of the study reach at Anadarko, Okla., and one at the lower end at Alex, Okla. (fig. 13-1). Tributary sampling stations were established at the gaging stations at

Tonkawa Creek, Salt Creek, East Bitter Creek, West Bitter Creek, and the Little Washita River. Chemical analyses of water, soil, and geologic samples were performed by USGS and locally by ARS.

Climate effects on stream salinity.—This first study determined the long-term trends in average

salinity levels at the main stem streamflow stations. Generally, this included the area in southwestern Oklahoma between Carnegie and Durwood (fig. 13-1) from 1954 to 1967. The specific objectives of the study were to (1) determine salinity trends in the upper Washita River basin and (2) identify the causative factors and evaluate their contribution if a major increase in salinity were observed (Pionke 1970). This study showed that there was an increase in average salinity of the Washita River for the period studied and that climate exerted the most influence on this change. However, part of the increase was attributed to changing land use, possibly more so than to the introduction of numerous impoundments in upstream locations. Two of the most important observations made in this study were the ineffectiveness of using previous records to predict salinity levels or of implying possible cause and effect relationships where several potentially dominating watershed characteristics were changing simultaneously and rapidly over the period of record.

Effects of hydrologic variables on predicting salinity.—In further studies of climatic and hydrologic variables as predictors of stream salinity, streamflow was found to be poorly related to salinity in some streams (Pionke and Nicks 1970). Using data collected at West Bitter Creek watershed in the study area and at Beaver Creek adjacent to the study area, direct measures of precipitation, both monthly and maximum daily rainfall, were better than streamflow as predictors of salinity. Thus, routinely collected meteorological data could better or more easily be used to predict stream salinity from watersheds where flow records are not commonly available. This is generally the case for watersheds more directly responsive to rainfall, i.e., primarily those less than 500 square miles in area.

Later studies were directed at improving the prediction of salinity when using only streamflow (Pionke et al. 1972). A model was developed that uses components of surface and base flow to produce improved estimates of salinity. In this model

$$\ln(s) = K - a(\ln Q_b) - b(Q_s/Q_b), \quad (1)$$

where s is the mean monthly salinity (micromhos per centimeter times 0.6), K is a constant that can be interpreted as the logarithm of the maximum salt concentration, Q_s and Q_b are mean monthly surface and base flow in cubic feet per second ob-

tained from flow component separation applied to mean daily flow, and a and b are constants fitted by regression.

A significant feature of this model is the use of the constant K , which is a measure of the maximum salinity of streamflow from the particular watershed being modeled. Because the value of K is the point at which dilution of salinity in the model starts, this constant represents the geologic measure of the salinity of a watershed and could be determined and used as a salinity index. The use of this model requires measures or estimates of Q_s and Q_b . Thus, the model lends itself to incorporation into a system of models being used today for hydrologic transport simulation.

The effects of impoundments on the salinity and quantity of stored water was the subject of a study completed in 1974 (Pionke and Workman 1974). Using data from Soil Conservation Service floodwater-retarding structures on Sandstone Creek watershed in western Oklahoma, the effect of chemical and hydrologic processes was determined for two small reservoirs. The authors determined that the design size of such structures was critical on watersheds subjected to high evaporative losses and high concentrations of salt in streamflow. Thus, a structure designed for sediment and permanent hydrologic storage might not be best suited for salinity management of impounded or outflow waters.

This study showed that in such climates and geologies, the error in permanent pool design must be in underdesign rather than in overdesign if the lowest possible salinity of the impounded and outflow waters is to be maintained. Dilution by high quality runoff and short residence periods of impounded water are apparently critical factors in controlling salinization of impounded waters.

NUTRIENT RUNOFF

Nitrogen and phosphorus concentrations in runoff from seven cropland and four rangeland watersheds were measured, beginning in July 1972, for periods ranging from 3.5 to 5 years (Menzel et al. 1978, Olness et al. 1980). Runoff amounts and sediment yields (see section 9) were also measured from these watersheds, continuing measurements that were begun in 1966 (Rhoades et al. 1975).

The cropland watersheds were on nearly level alluvium at the Oklahoma South Central Research Station at Chickasha. The soils were McLain and Reinach silt loams or silty clay loams. The crops were cotton, wheat, or alfalfa during the period of measurement.

The rangeland watersheds were on 3-percent upland slopes on privately owned ranches. The soils were Renfrow, Grant, and Kingfisher silt loams. Two of the watersheds were generally grazed within recommended limits and two were generally overgrazed. The overgrazed watersheds had some actively eroding gullies.

Nutrient concentrations.—The average flow-weighted nutrient concentrations for the period of record (1972–76) are shown in table 13-1, along with average annual runoff and sediment yields for longer periods (see section 9). Rainfall and runoff were above the long-term average while nutrient concentrations were being measured. Sediment yields from most watersheds were also above average during this period. Since Kjeldahl-N and total phosphorus in runoff were primarily associated with suspended sediment, the concentrations that we measured were probably somewhat higher than normal for the land uses in this area. However, the concentrations of nitrate nitrogen and soluble phosphorus did not vary significantly with annual runoff amounts; thus, the measured concentrations should represent the respective land uses. The concentrations of nutrient forms shown in table 13-1 are slightly lower than those that have been measured in other agricultural areas of the United States. The

concentrations of nitrate nitrogen are much lower than 10 milligrams per liter, the level at which nitrate becomes of concern in drinking water. Nevertheless, the concentrations of nitrate nitrogen and soluble phosphorus are high enough to support rapid growth of aquatic plants and thus to be of concern in eutrophication. Average annual nutrient yields per hectare ranged from 1.4 kilograms of nitrogen and 0.4 kilogram of phosphorus from R-6 to 10.5 kilograms of nitrogen and 5.6 kilograms of phosphorus from C-4. These yields do not represent serious losses of soil fertility.

Deposition of nitrogen and phosphorus in rainfall was measured with samples taken in a collector that was kept covered except during rainfall. The rainfall-weighted average concentrations in milligrams per liter were nitrate nitrogen, 0.23; ammoniacal nitrogen, 0.26; soluble phosphorus, 0.004; and total phosphorus, 0.019. The average annual deposits of total nitrogen and phosphorus were 5.3 and 0.15 kilograms per hectare, respectively. Thus, more nitrogen was deposited in rainfall on most of the watersheds than was lost in runoff.

Effects of fertilizer.—Watersheds R-5 and R-7 were fertilized on May 19, 1975 with 85 kilograms of nitrogen and 75 kilograms of phosphorus per hectare in a bulk-blended mixture. Four days later, a heavy storm produced 3.6 and 5.4 centimeters of runoff on the respective watersheds. About 4 percent of the applied fertilizer ran off from both watersheds. The effect of this event can be seen in the nutrient concentrations shown

Table 13-1.—Sediment yield and nutrient concentrations in runoff from unit-source watersheds at Chickasha, Okla.

Watershed and use	Annual runoff (cm)		Annual sediment yield (t/ha)		Average flow-weighted nutrient concentration (mg/l), 1972–76 ¹			
	1966–76 ¹	1972–76	1966–76 ¹	1972–76	Kjeldahl-N	Nitrate-N	Total P	Soluble P
C-1, cotton	7.3	11.2	1.3	1.9	3.6	0.52	2.1	0.40
C-3, cotton	11.3	14.8	3.8	4.2	5.1	.82	3.8	.77
C-4, cotton	9.8	14.6	3.9	6.0	5.8	1.40	3.8	.67
C-5, wheat	6.0	11.0	.9	1.4	4.3	.87	1.7	.32
C-6, wheat	6.4	10.8	1.5	2.4	4.8	.91	1.9	.24
C-7, alfalfa	5.8	7.2	1.9	.5	3.0	1.11	1.6	.68
C-8, alfalfa	4.0	8.2	.5	.5	3.1	.46	1.1	.36
R-5, properly grazed . .	4.1	6.4	.1	.1	2.7	.26	1.6	1.10
R-6, properly grazed . .	4.4	7.1	.3	.6	1.7	.26	.6	.39
R-7, overgrazed	12.9	17.3	9.0	13.4	4.1	.46	1.6	.39
R-8, overgrazed	10.1	13.9	11.5	15.6	3.3	.23	1.1	.04

¹Period of record ended in December 1975 for watersheds C-1, C-7, and C-8; in June 1976 for watersheds C-3–C-6; and in June 1977 for watersheds R-5–R-8.

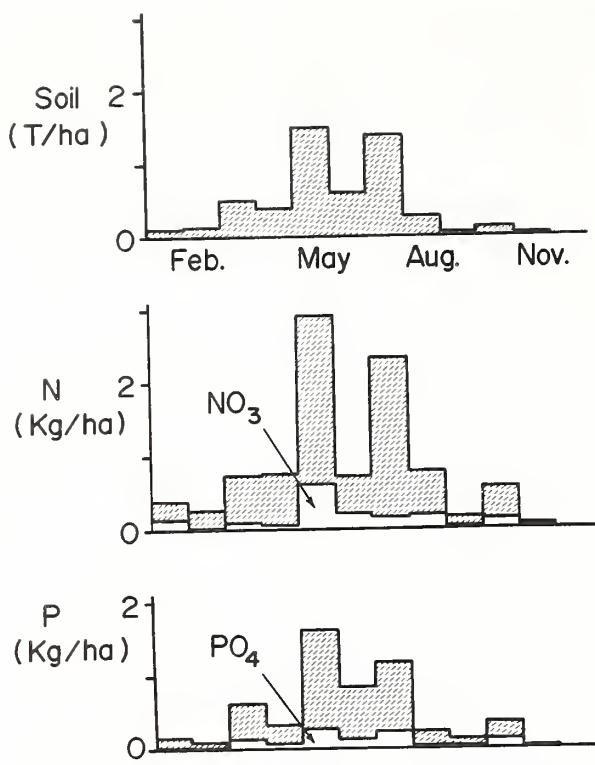


FIGURE 13-2.—Monthly patterns of sediment and nutrient yields from watersheds planted to cotton, averages for July 1972 to June 1976.

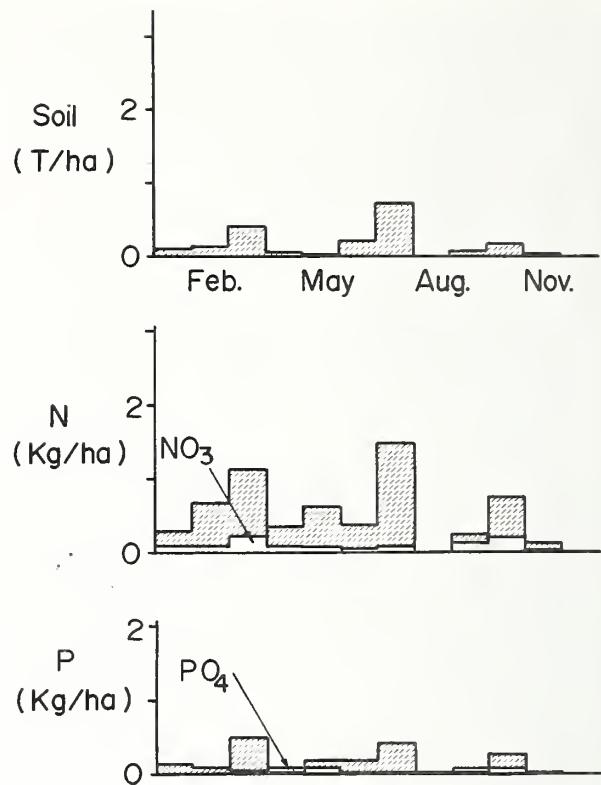


FIGURE 13-3.—Monthly patterns of sediment and nutrient yields from watersheds planted to wheat, averages for July 1972 to June 1976.

in table 13-1. Nitrate nitrogen concentrations were not affected, since the nitrogen was applied in the ammonium form and had little effect on the concentrations of either Kjeldahl-N or nitrate nitrogen in runoff after the first storm. However, soluble phosphorus concentrations in runoff from the fertilized watersheds in 1977 were still 3 times those from the unfertilized watersheds. About 20 percent of the applied nitrogen and 10 percent of the applied phosphorus were taken up in increased herbage growth in 1975. Favorable rainfall enhanced the yield response to fertilizer, which amounted to about 2 metric tons of additional herbage on each watershed.

Fertilizer use on cotton increased the soluble phosphorus concentrations from watersheds C-3 and C-4. From 1966 to 1976, an average of 27 kilograms of phosphorus per hectare was applied annually on cotton, compared to 7 kilograms of phosphorus per hectare on wheat. The additional amount of phosphorus discharged in runoff amounted to <5 percent of the fertilizer applications.

Enrichment ratios.—Nutrients were enriched in the sediment that was carried in runoff. The enrichment ratio is defined by Menzel (1980) as concentration of nutrient in the sediment divided by its concentration in the watershed soil. The degree of enrichment was higher for storms with lower sediment discharges. The relationship is described approximately by the following equation:

$$\ln (ER) = a + b \ln (sed), \quad (2)$$

where ER is the enrichment ration, sed is the sediment discharge per storm in kilograms per hectare, and a and b are constants that were determined by regression analysis for cotton, wheat, and range, with the following results:

Land use	Nitrogen ER		Phosphorus ER	
	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
Cotton	1.85	-0.20	1.57	-0.13
Wheat	2.95	-0.44	2.40	-0.33
Range	1.50	-0.28	2.32	-0.26

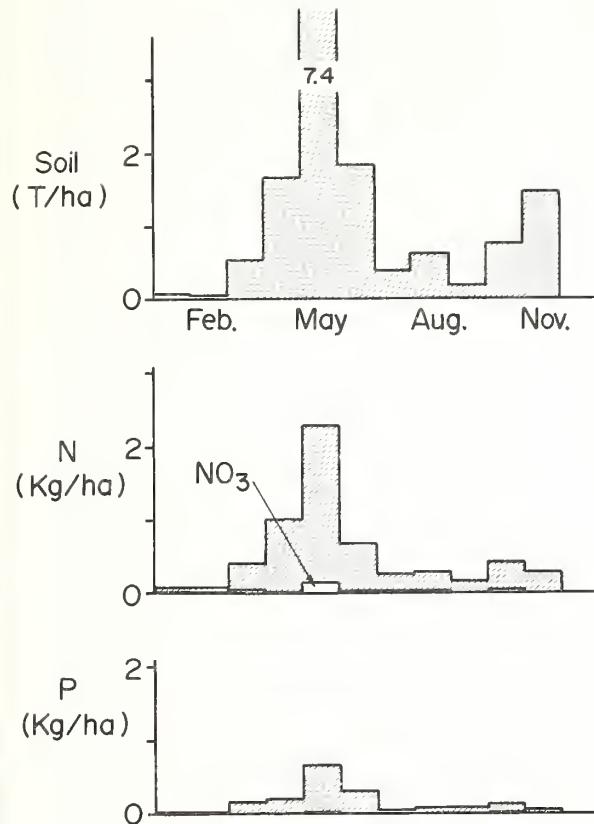


FIGURE 13-4.—Monthly patterns of sediment and nutrient yields from unfertilized poor-range watersheds, averages for July 1972 to June 1977.

The differences in slopes (*b*) are statistically significant and may be related to effects of cover on the erosion process and composition of runoff. However, more research is needed to understand these effects for prediction and modeling purposes.

Annual and monthly variability.—Variability is an important characteristic of sediment and nutrient yields from the Chickasha watersheds (Menzel et al. 1978). Maximum annual sediment yields ranged from 2.5 to 4.5 times the average yields for different land uses. Maximum annual nutrient yields were about twice the average yields for most nutrient forms and land uses. It was not unusual for half of the annual sediment and nutrient yields to occur in one event.

The monthly patterns of sediment and nutrient yields are shown in figures 13-2—13-5. The largest monthly yields occurred in May from range watersheds and in July from wheat watersheds. For the cotton watersheds, the May and July

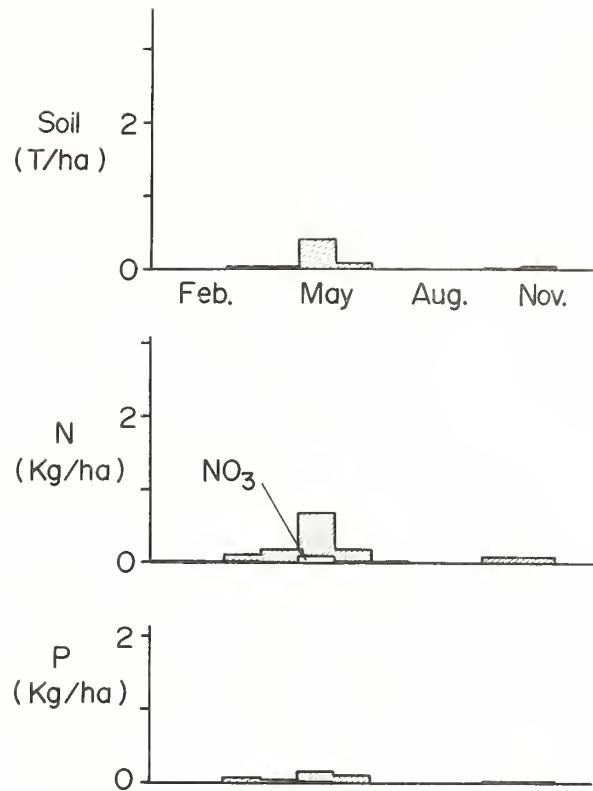


FIGURE 13-5.—Monthly patterns of sediment and nutrient yields from unfertilized good-range watersheds, averages for July 1972 to June 1977.

peaks were about equal. It should be emphasized that these results were strongly influenced by a few large runoff events. However, it appears typical for greater yields of sediment and nutrients to occur when ground cover is sparse or absent.

The unshaded areas in figures 13-2—13-5 represent nitrate nitrogen and soluble phosphorus. Greater discharges of these forms of nutrients occurred from cotton and wheat than from range. The monthly pattern of discharges seems to have been influenced by fertilization, and in the case of nitrate nitrogen, by cultivation. For cotton, a complete fertilizer was incorporated into the soil before planting in May. For wheat, very little phosphorus fertilizer was used. The nitrogen application was split, about half being incorporated before planting in October and half being top-dressed in winter. The preparation of seedbeds for cotton and wheat promotes mineralization and nitrification of organic soil nitrogen, which ac-

cumulates as nitrate until it is used by the growing crop.

SUMMARY

Average annual salinity of the Washita River at Carnegie increased from 500 to 1,000 parts per million of total dissolved solids between 1954 and 1967. Most of the increase was primarily attributed to climatic changes, secondarily to land-use changes but not to impoundment. In more detailed studies on West Bitter Creek and Beaver Creek, precipitation was a better predictor of stream salinity than was streamflow. Predictions using streamflow data were improved by separating surface- and base-flow components and adding the maximum salinity of streamflow for each particular watershed. The permanent pool design of floodwater-retarding structures is critical to the salinity buildup of impounded waters. Overdesign reduces dilution and flushing of impounded waters by the generally high-quality inflows associated with storm runoff and subjects the retained water to greater evaporational losses.

Average annual nutrient losses in runoff from grassland and cropland watersheds ranged from 1.4 to 10.5 kilograms per hectare of nitrogen and from 0.4 to 5.6 kilograms per hectare of phosphorus. On some of the watersheds more nitrogen was deposited in rainfall than was lost in runoff, but phosphorus deposited in rainfall was not significant. Nutrient runoff was highly variable from year to year, with maximum annual losses being about twice the average values.

On fertilized watersheds, runoff losses amounted to <5 percent of the applied fertilizer. The losses of soluble nutrients were greater from cropland than from grassland. Most of the soluble nutrient

loss occurred near crop planting time, in May with cotton and in October with wheat. A second peak in soluble nitrogen loss occurred in March with wheat after a winter topdressing had been applied.

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Section 14.—Hydrologic Transport Modeling

INTRODUCTION

The hydrologic, erosion-sedimentation, and chemical-transport research programs conducted at Chickasha, Okla., during the 18-year period (1961-78) compiled a data base that, with supportive information, is possibly the most complete for hydrologic modeling research in the Southern Great Plains. Records of rainfall, runoff, sediment and chemical transport, ground-water level, evaporation, and soil moisture were collected on watersheds ranging in size from a few acres to 200 square miles. It was not until the early 1970's that the real importance of modeling was appreciated as a tool to study man's influence on the water-resource environment. After the passage of Public Law 92-500 (Clean Waters Act) in 1972, much emphasis was placed on modeling the total water transport regime, including not only water transport but also sediment and chemicals in the water.

In 1974 at Chickasha, a hydrologic modeling research program was initiated to evaluate the existing hydrologic models, to modify those models for use on basins in this area, and to develop new models based on results of these tests and evaluations. Since that time, several models have been evaluated using watershed data collected at Chickasha. The following discussion covers developments in the testing and evaluation project.

The first model to be evaluated was the U.S. Department of Agriculture Hydrograph Laboratory (USDAHL) 1974 model (Holton et al. 1975). The work was continued with a newer version in 1975 with support funds added by the joint Agricultural Research Service (ARS)-Soil Conservation Service (SCS) Hydrology Advisory Committee under Reimbursable Cooperative Agreement No. 121404032, Hydrologic Modeling. The objective of the study was to evaluate the model under conditions that the normal user of such models would incur, i.e., using only available data

such as National Weather Service rainfall data, SCS soil survey data, and U.S. Geological Survey (USGS) topographic maps for the inputs, and to evaluate model parameters. It was assumed that no calibration of parameters could be done because observed data usually would not be available to the user on most watersheds.

Most of the work was centered around evaluating the results of the initial runs. The model was not altered or modified to improve results; however, some areas of parameter estimation were identified where modifications were needed. Data sets consisting of hourly rainfall, daily temperature, and evaporation were compiled, and parameter sets were evaluated for each of 12 watersheds, 10 within the experimental area and 2 in eastern Oklahoma at Wilburton (Fourche Maline Creek) and Sallisaw (Sallisaw Creek). Land use ranged from a single crop of range plants, irrigated cotton, or dryland wheat to multiple land use, including rangeland, pasture, row crops, small grains, timber, and strip mining on the large watersheds. Table 14-1 summarizes some characteristics of the 12 watersheds.

USDAHL HYDROLOGIC MODEL

Precipitation data.—The model requires a single precipitation input, which may be breakpoint-interval, hourly, or daily data. In this study, hourly rainfall was used for each watershed. Breakpoint-rainfall data sets were completed and used in later runs for the smaller watersheds. At least one rain gage in the drainage area was used for each ARS watershed. National Weather Service hourly rainfall data from stations near Sallisaw Creek and Fourche Maline Creek watersheds in eastern Oklahoma were the only available data for these watersheds.

Weekly pan-evaporation and temperature data.—Mean daily values of air temperature mea-

Table 14-1.—Summary of characteristics of 12 watersheds used in model evaluation

Watershed	Area (acres)	Years of record	No. land uses	No. soils	Data source ¹	Annual rainfall (in)	Annual runoff (in)
Sallisaw	116,480.0	8	3	50	NWS, USGS	38.66	8.441
Fourche Maline .	78,080.0	12	7	² 4	NWS, USGS	46.17	12.735
West Bitter	38,020.0	10	5	32	ARS	26.31	1.501
Delaware	25,660.0	12	4	17	ARS	26.32	.756
East Bitter	22,530.0	11	6	32	ARS	30.40	2.918
Big Dry	4,844.8	13	4	32	ARS	27.53	2.195
Little Dry	536.2	13	4	9	ARS	27.53	1.275
C-4	29.9	8	1	2	ARS	27.58	3.396
R-5	23.7	6	1	3	ARS	27.65	1.065
R-7	19.2	8	1	2	ARS	30.27	5.976
C-6	13.0	8	1	3	ARS	27.58	2.479
C-5	12.7	8	1	3	ARS	27.58	2.235

¹NWS, National Weather Service. USGS, U.S. Geological Survey. ARS, Agricultural Research Service.

²From Soil Conservation Service generalized soils map.

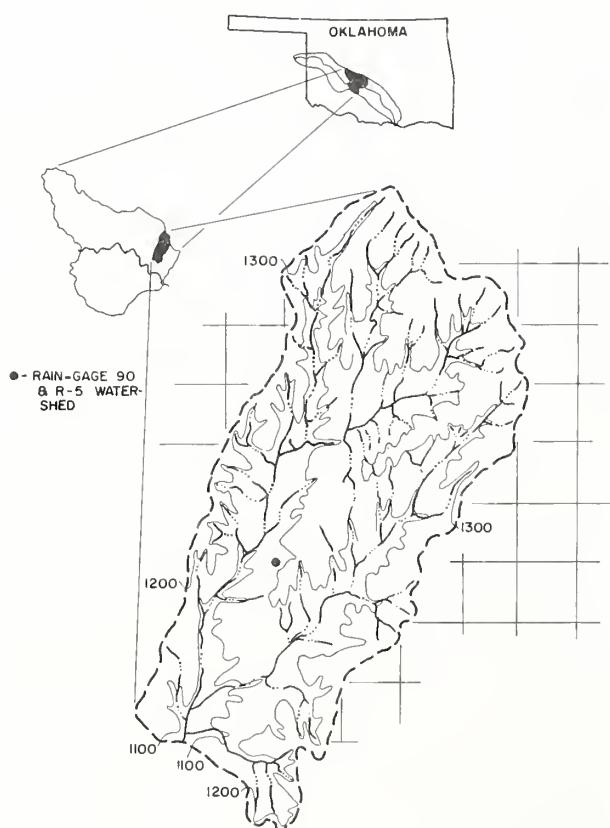


FIGURE 14-1.—East Bitter Creek watershed, showing elevation (feet above m.s.l.) contours and section (square mile) lines.

sured at three ARS climatological stations in the study area were used to compute the weekly air-temperature values required by the model. In the case of the eastern Oklahoma watersheds, the mean daily temperatures at the National Weather Service climatological stations at Wister and Tenkiller Lakes were used, as well as monthly class A pan-evaporation data from these stations (U.S. National Oceanic and Atmospheric Administration 1974). Weekly values of temperature and evaporation for model input were calculated from the daily values. The class A pan-evaporation data base for ARS watersheds was calculated from meteorological data measured at the three ARS climatological stations.

Map data.—In addition to the historical climatic data required by the model, 71 parameter values pertaining to watershed zones, flow routing, subsurface flow, cascading, and land use must also be evaluated. Examples of these parameters are given in table 14-2. Also, 10 additional parameter values for each land use must be determined. For the watersheds evaluated in this study, the total number of parameters evaluated ranged from 81 to 151, as shown in table 14-3. These parameters, combined with the many soils found on large watersheds, presented a formidable task in lumping these data into a single parameter estimate.

A great deal of the data preparation required in using the USDAHL-74 model involves the map-

Table 14-2.—Values of lumped parameters used by the USDAHL hydrologic model for East Bitter Creek watershed

WATERSHED PARAMETERS														
ACRES = 22,530.0		NUMBER OF ZONES = 3.0			NUMBER OF ROUTING COEFFICIENTS = 5.0									
		NUMBER OF CROPS = 6.0			DEEP GROUND WATER RECHARGE = .00015 IN/HR									
GENERAL ZONE PARAMETERS														
ZONE	% AREA	SLOPE LENGTH (FT)	% SLOPE	INFILTRATION (IN/HR)	TOP	SOIL DEPTH TOTAL	% INITIAL SOIL MOISTURE TOP TOTAL							
1	21.7	1,452.0	3.3	.150	8.4	48.4	29.0 30.0							
2	61.2	1,683.0	5.3	.160	8.2	44.2	29.0 30.0							
3	17.1	2,310.0	2.7	.180	8.4	45.3	29.0 30.0							
SOIL PARAMETERS														
ZONE	UPPER		LOWER											
ZONE	TOTAL POROSITY	FIELD CAPACITY	WILT POINT	CRACKING	TOTAL POROSITY	FIELD CAPACITY	WILT POINT	CRACKING						
1	42.0	30.6	11.5	0.0	44.0	33.9	17.0	0.0						
2	42.0	30.5	11.5	0.0	43.1	32.8	15.2	0.0						
3	41.7	30.2	11.4	0.0	42.0	31.9	14.4	0.0						
ROUTING PARAMETERS														
CHANNEL ROUTING DELTA TIME = .25 HR		CHANNEL COEFFICIENT = 1.76			INITIAL STREAMFLOW = .0001 IN/HR									
SUBSURFACE PARAMETERS														
REGIME		Q - MAX (IN/HR)		COEFFICIENT (HRS)										
1		.00415		3.62										
2		.00273		7.38										
3		.00101		17.16										
4		.00042		1,246.78										
CASCADING PARAMETERS														
ZONE	TO NEXT ZONE		REST GOES TO											
1	40.0		CHANNEL											
2	20.0		CHANNEL											
3	100% TO CHANNEL													
LAND USE PARAMETERS														
PARAMETER	ROW CROP	SOW CROP	ALFALFA	PASTURE	RANGE	TIMBER								
A VALUE	.15	.25	.30	.30	.80	.80								
CROP VD	.05	.05	.05	.10	.10	.10								
ET/EP	1.20	1.30	1.20	1.20	1.20	2.00								
ROOT DEPTH	24.00	18.00	60.00	24.00	30.00	72.00								
UPPER TEMPERATURE	100.00	90.00	90.00	80.00	90.00	90.00								
LOWER TEMPERATURE	50.00	35.00	50.00	35.00	39.00	50.00								
LAND USE AREA BY PERCENT OF ZONE														
ZONE	ROW CROP	SOW CROP	ALFALFA	PASTURE	RANGE	TIMBER								
1	1.4	2.6	1.6	8.5	85.9	0.0								
2	1.3	2.3	1.6	12.5	78.3	4.0								
3	12.1	21.3	13.9	6.7	40.0	5.2								

ping and determination of soil, land-use, and other watershed physical characteristics. On small watersheds, this is not a significant problem; however, on large watersheds with many soil and land uses, such determination becomes a major part of the parameter estimation. Topographic soil maps were available for the watersheds selected in this study. An automatic map-digitizing system was available to digitize and then calculate the parameter areas on the maps, which reduced the amount of work considerably. However, a considerable amount of work was required in outlining watershed-zone, soil, and land-use boundaries on the topographic and land-use maps before digitizing. The method used in this

Table 14-3.—Total number of parameters estimated for each of 12 watersheds used in model evaluation

Watershed	Number of land uses	Number of parameters
Sallisaw	3	111
Fourche Maline	7	151
West Bitter	5	131
Delaware	4	121
East Bitter	6	141
Big Dry	4	121
Little Dry	4	121
C-4	1	81
R-5	1	81
R-7	1	81
C-6	1	81
C-5	1	81

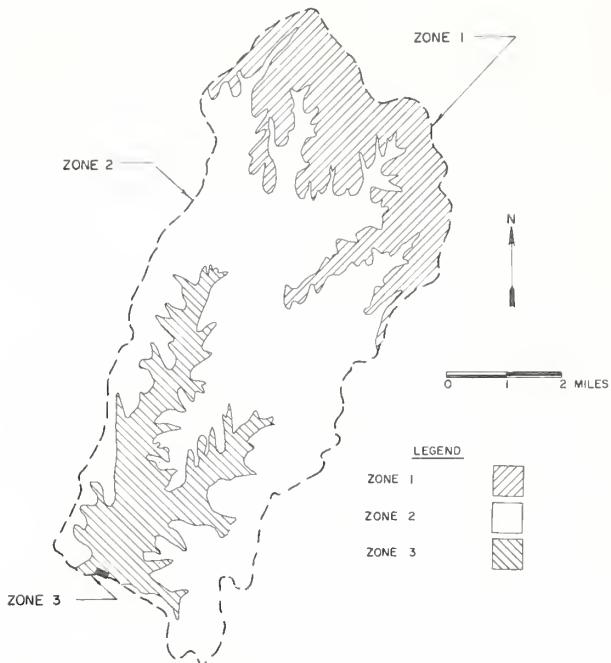


FIGURE 14-2.—Hydrologic zones of East Bitter Creek watershed.

study is illustrated in figure 14-1 with East Bitter Creek watershed.

This model divides watersheds into three hydrologic zones. The zones in the East Bitter Creek watershed (fig. 14-2) were chosen to represent the relatively flat uplands (zone 1), the steeper sloped midarea (zone 2), and the lower flat-bottom area (zone 3). The first step in developing the input information for the model is to determine total watershed area and the percentage of this area in each zone. This was accomplished for the larger watersheds by delineating the watershed and zone boundaries on a USGS 7.5-minute quadrangle map. Using the digitizing system, the areas were determined and the boundaries stored on magnetic tape as a series of Cartesian coordinates for replotting to a different scale. The topographic maps were also used to determine an average flow-path length and percentage of slope for each zone. Average flow length was determined by averaging the lengths of several flow paths perpendicular to contour lines extending from the upper zone edge to the channel or lower zone edge. The percentage of slope was calculated for these flow paths using the contour lines at the upper and lower ends of each line. These values were averaged to yield the mean slope parameter for each zone.

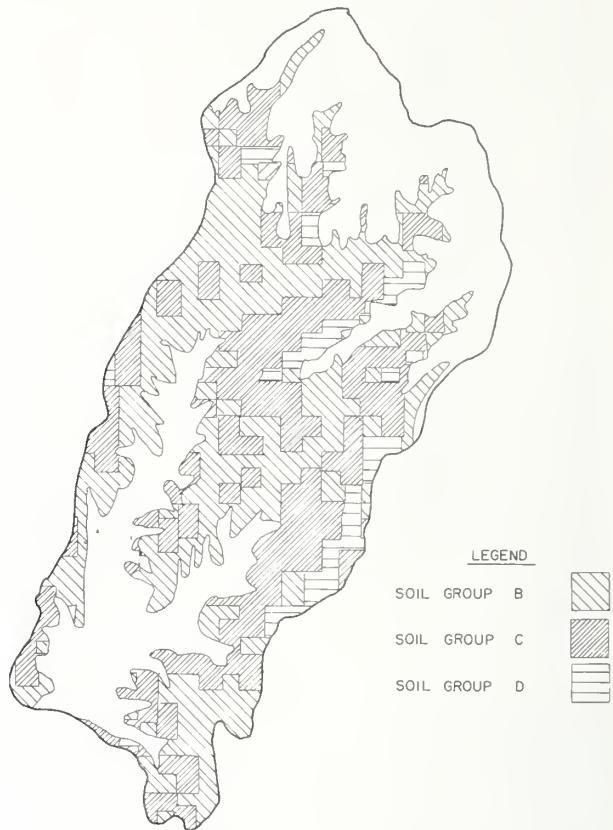


FIGURE 14-3.—Hydrologic soil groups in zone 2 of East Bitter Creek watershed. Group B, soils having moderate infiltration rates when thoroughly wetted. Group C, soils having slow infiltration rates when thoroughly wetted. Group D, soils having very slow infiltration rates when thoroughly wetted (high runoff potential).

SCS uses a Map Information Assembly and Display System (MIADS) that contains soil and land-use information in 40-acre cells (U.S. Soil Conservation Service 1975). The watershed and zone boundaries were replotted using a computer plotter to match the scale of the MIADS series maps (Amiden 1966). Using the plotted boundary maps as overlays, soil groups were transferred from the MIADS maps to the overlays. Soil depth, infiltration, and texture values were obtained from SCS county soil survey reports, soil series line sheets, and soil series interpretations. Values for total porosity, field capacity, and wilting point were estimated from the texture of each soil. Depths of the upper and lower layers of each soil on the watershed were obtained from soil survey reports.

SCS has four hydrologic classes for soils. Selection of the infiltration parameter is based upon

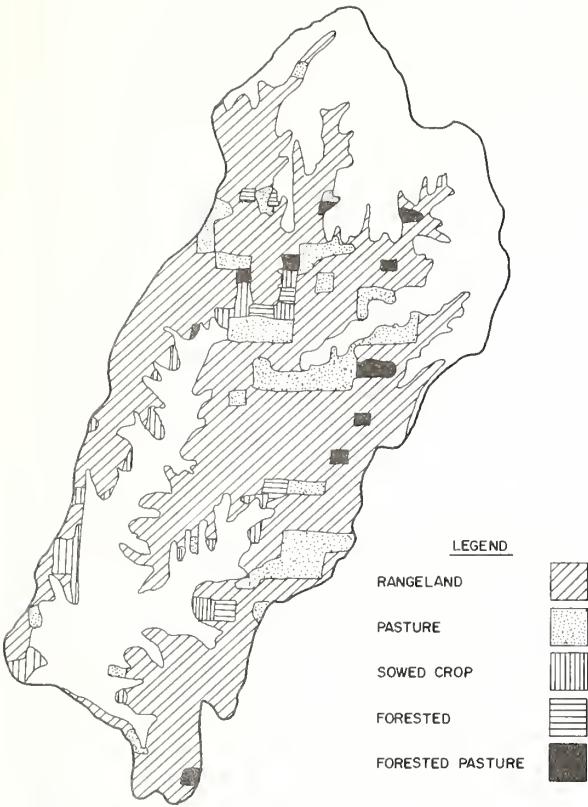


FIGURE 14-4.—Distribution of land uses in zone 2 of East Bitter Creek watershed.

the hydrologic class. Since numerous soils exist on the watersheds (table 14-1), the soils were first lumped by hydrologic class and then by zone. Figure 14-3 shows the distribution of soils in zone 2 of the East Bitter Creek watershed according to hydrologic class. The average soil parameters were calculated for each hydrologic class by weighing the parameter for each soil on the basis of its area relative to the area of all the soils in its hydrologic class. Zone values were then derived by weighing each hydrologic class by its area within the zone.

Land-use data for the larger watersheds were also taken from the MIADS series maps. Watershed and zone boundaries were overlayed and the data transferred for each zone. Figure 14-4 shows the distribution of five land uses in zone 2 of East Bitter Creek. The MIADS classifications of land use are general, such as row crop, sowed crop, pasture, range, etc. Therefore, lacking more detailed information, it was assumed that all areas designated row crop were planted in the

dominant row crop grown in that area (cotton on East Bitter Creek watershed). The same assumptions were made for sowed crop (wheat on East Bitter Creek watershed). The model requires as input the percentage of a zone area in each land use. These values were determined directly by using the digitizing system to measure areas.

The model requires estimates of six cropping factors for each land use. They are A , the basal area of vegetation; Vd , the detention storage in inches; ET/EP , the ratio of evapotranspiration to pan evaporation; root depth; and maximum and minimum cardinal temperature for each crop. These factors were determined for each land use with the aid of tables given in the USDAHL manual. However, in some cases where tabular material for a land use was not given, these factors had to be estimated. For example, the cardinal temperatures for certain crops, basal areas, and urban areas were cases where estimates had to be made. We also noted that, since weekly mean temperatures were used, the cardinal temperatures had to be a weekly value. The cardinal temperature selected should be lower than the maximum and higher than the minimum values given in the manual. Tillage data were approximated for the dominant crop in each major land-use category by using local average dates for plowing, planting, and harvesting. Table 14-2 shows some of the lumped parameters used for the East Bitter Creek watershed.

Flow and routing data.—The USDAHL-74 model normally uses recession constants derived from observed hydrographs. Flow intervals were available in the study from both ARS and USGS (U.S. Geological Survey 1969) records. On the larger watersheds, five recession constants for flow rate and slope were derived and used in the model. However, on the smaller watersheds only two sets, and in some instances only one set, of recession values were used. Because all five values are usually needed in the model, downstream stations were used to estimate the recession constants not present in observed flow records. Monthly and yearly flow values for each watershed were calculated for use in the statistical evaluation.

In this study, observed flow records were available for each of the 12 watersheds from ARS and USGS (U.S. Geological Survey 1969). However, for ungaged watersheds these parameters would have had to be estimated from nearby watersheds or from regional flow characteristics. The groundwater recharge constant used was estimated from

Table 14-4.—Areas controlled by farm ponds and flood-control structures on five of largest watersheds in study

Watershed	Area (acres)	Areas behind farm ponds			Areas behind flood-control structures		
		No. struc- tures	No. acres	Percentage of total area	No. struc- tures	No. acres	Percentage of total area
Little Dry	536	2	110	20.7	1	320	60.0
Big Dry	4,845	11	1,516	31.3	5	3,052	63.0
Delaware	25,660	39	2,168	8.45	0	0	.0
East Bitter	22,530	111	6,804	30.2	7	4,711	20.9
West Bitter	38,020	247	15,100	39.9	11	12,948	34.0

measurements made within the study area. However, as with recession constants, these values would have had to be estimated from regional ground-water characteristics for watersheds in un-gaged areas.

Another characteristic of Southern Great Plains watersheds, which is not incorporated into the USDAHL model and which has a temporal and spatial effect on runoff simulation, is the storage of overland and channel flow in farm ponds and flood-retarding reservoirs. Table 14-4 lists the total number of these structures on each of the five largest watersheds in the study and the area they control. The area of watersheds controlled ranges from 8 to 40 percent for farm ponds and from 21 to 63 percent for flood-retarding structures. It is not currently known what effect the areas controlled by these structures have on model results. However, the model in its present form does not account for the variance in storage in these reservoirs. Further calibration of the model on watersheds with structures should include a routine to estimate their effect on model results.

Other areas where problems were encountered in using this model were the user manual, estimating overland flow length, and differences in rainfall-input time scale.

The user manual was not always clear on the meaning of certain parameters. As noted earlier, cardinal temperature data used in the growth index must reflect the weekly average temperature of the input data rather than the daily value given in the table. There are other parameter definition problems in the manual, such as the ground-water recharge constant; perhaps some representative value should be given. In general, the manual should be rewritten.

Results and discussion.—After compilation and initial evaluation of the model parameters, simulation runs were computed using the entire length of record for each watershed. Table 14-5 lists the monthly and yearly results of initial model runs on each of the 12 watersheds. Length of the input records ranged from 8 to 12 years. Annual rainfall and runoff from the observed records ranged from 26 to 46 inches and 0.75 to 12 inches, respectively (see table 14-1). The coefficient of determination was calculated as a measure of dispersion between the observed and predicted water yields for monthly and yearly intervals; the coefficient ranged from 0.18 to 0.91. There was generally less variability in the soil and land-use parameters. Exceptions to this were the R-5 range watershed, where the coefficient was unusually low, and East Bitter Creek watershed, which had the highest coefficient. Though these results may appear discouraging, it must be remembered that they are uncalibrated results and should not be compared with results from models that employ optimization and thus require records from the watershed.

The difference between the predicted yield and the observed yield as a fraction of the observed yield is given on the bottom line of table 14-5. Since the watersheds are arranged according to size, it is obvious that the relative size or sign of the difference is not related to watershed size. The most significant observation of these statistics is that the overestimates are much larger than the underestimates. A skewed distribution of data might be expected because zero runoff is the lower bound.

Other outputs from the model were compared with observed data. Figure 14-5 is an example of

Table 14-5.—Monthly and yearly results of uncalibrated initial model runs on each of 12 watersheds in study¹

Statistical parameter	Sallisaw	Fourche Maline	West Bittern	Delaware	East Bittern	Big Dry	Little Dry	C-4	R-5	R-7	C-6	C-5
	MONTHLY, OBSERVED											
MONTHLY, USDAHL PREDICTED												
Mean runoff	0.703	1.061	0.125	0.063	0.243	0.182	0.106	0.282	0.088	0.498	0.206	0.186
Standard deviation	.94	1.38	.21	.08	.35	.29	.20	.56	.23	.75	.48	.44
YEARLY, OBSERVED												
Mean runoff	0.317	0.911	0.121	0.309	0.722	0.616	0.478	0.238	0.068	0.275	0.604	0.613
Standard deviation	.65	1.61	.22	.71	1.16	.88	.75	.54	.18	.61	.91	.92
Standard error	.94	1.20	.13	.77	1.07	.81	.75	.28	.19	.40	.76	.80
CD ²	.22	.49	.66	.36	.58	.58	.38	.76	.38	.81	.57	.54
YEARLY, USDAHL PREDICTED												
Mean runoff	8.441	12.734	1.501	0.756	2.917	2.194	1.275	3.395	1.064	5.976	2.479	2.234
Standard deviation	5.29	6.17	.47	.53	2.42	1.96	1.25	2.18	.61	3.56	2.36	2.21
PREDICTED/OBSERVED³												
OBSERVED												
Mean runoff	3.801	10.941	1.461	3.717	9.264	7.392	5.743	2.858	0.817	3.305	7.254	7.356
Standard deviation	2.66	7.53	.52	3.77	6.73	4.78	3.74	1.65	.63	1.74	4.94	4.98
Standard error	6.34	5.83	.44	4.76	8.46	6.57	6.02	1.42	.78	3.97	6.36	6.84
CD ²	.80	.53	.42	.74	.91	.76	.18	.71	.22	.70	.84	.79
	-0.55	-0.14	-0.03	+3.9	+2.2	+2.4	+3.5	-0.16	-0.23	-0.45	+1.9	+2.3

¹Runoff values are in inches.

²CD, coefficient of determination.

³Difference between predicted and observed runoff values divided by the observed runoff value.

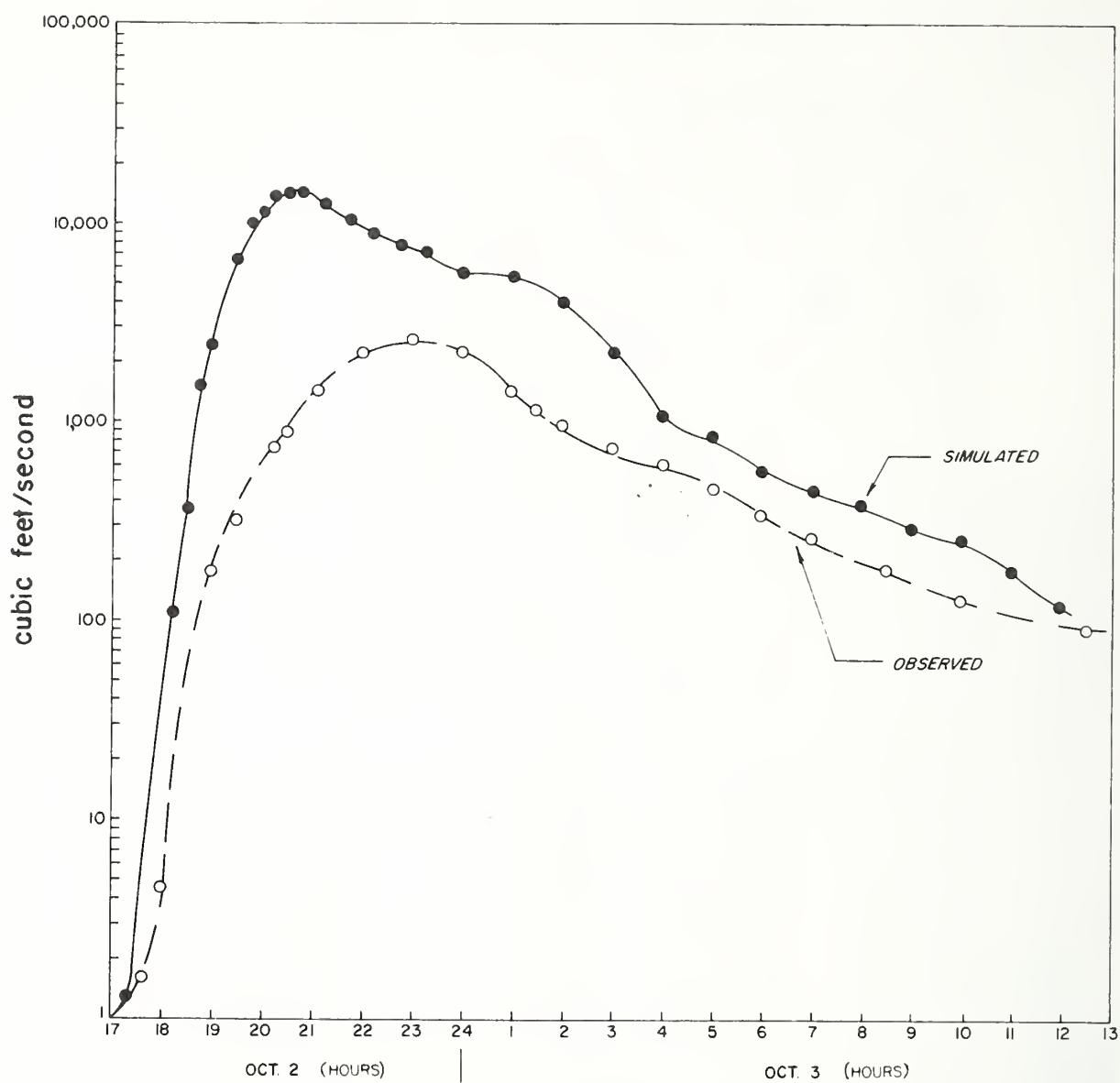


FIGURE 14-5.—Observed and simulated hydrograph for East Bitter Creek watershed on Oct. 2 and 3, 1971.

an observed and simulated storm hydrograph from the East Bitter Creek watershed. Note that the flow rate is on a log scale. Though there is a serious overestimation in peak flow rate, it is encouraging to note the close resemblance in both time and shape of the hydrograph. Such a response from an uncalibrated simulation indicates that only a few parameters may be in error.

Another output from the model that is useful for evaluation is the daily soil-moisture value for the upper and lower layers of the soil. Figure 14-6

is an example of the total soil moisture in the top 48 inches of zone 2 in the East Bitter Creek watershed. The observed data are the average values of four neutron-tube soil-moisture measurements made at 2-week intervals throughout the year on watershed R-5, which is located in zone 2 of East Bitter Creek watershed (fig. 14-1). The simulated values were computed daily.

The simulation of soil moisture was quite good, particularly considering the lumping that was necessary to develop composited percentage values of total porosity, field capacity, and

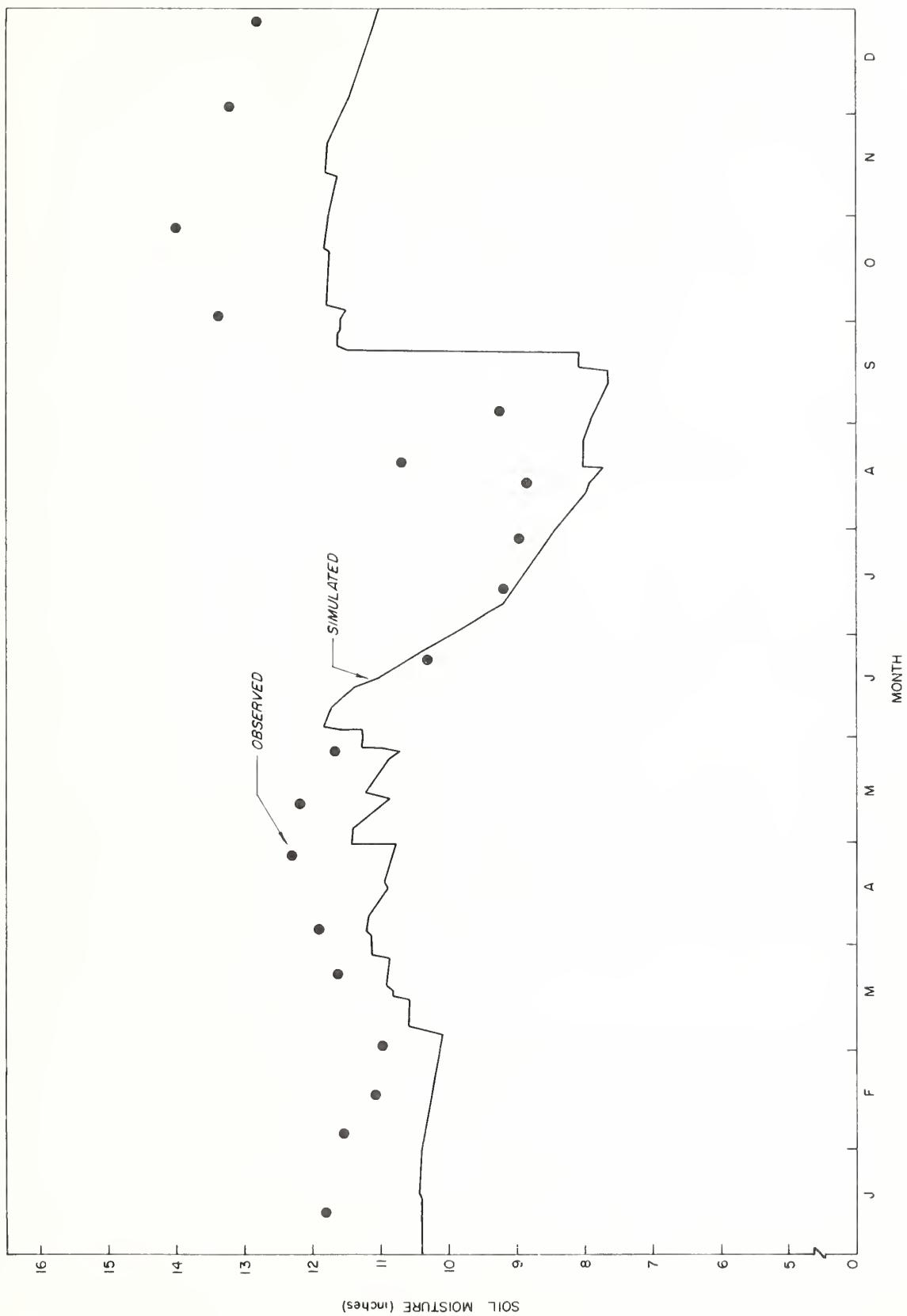


FIGURE 14-6.—Observed and simulated soil moisture in the top 48 inches of zone 2 in East Bitter Creek watershed during 1971.

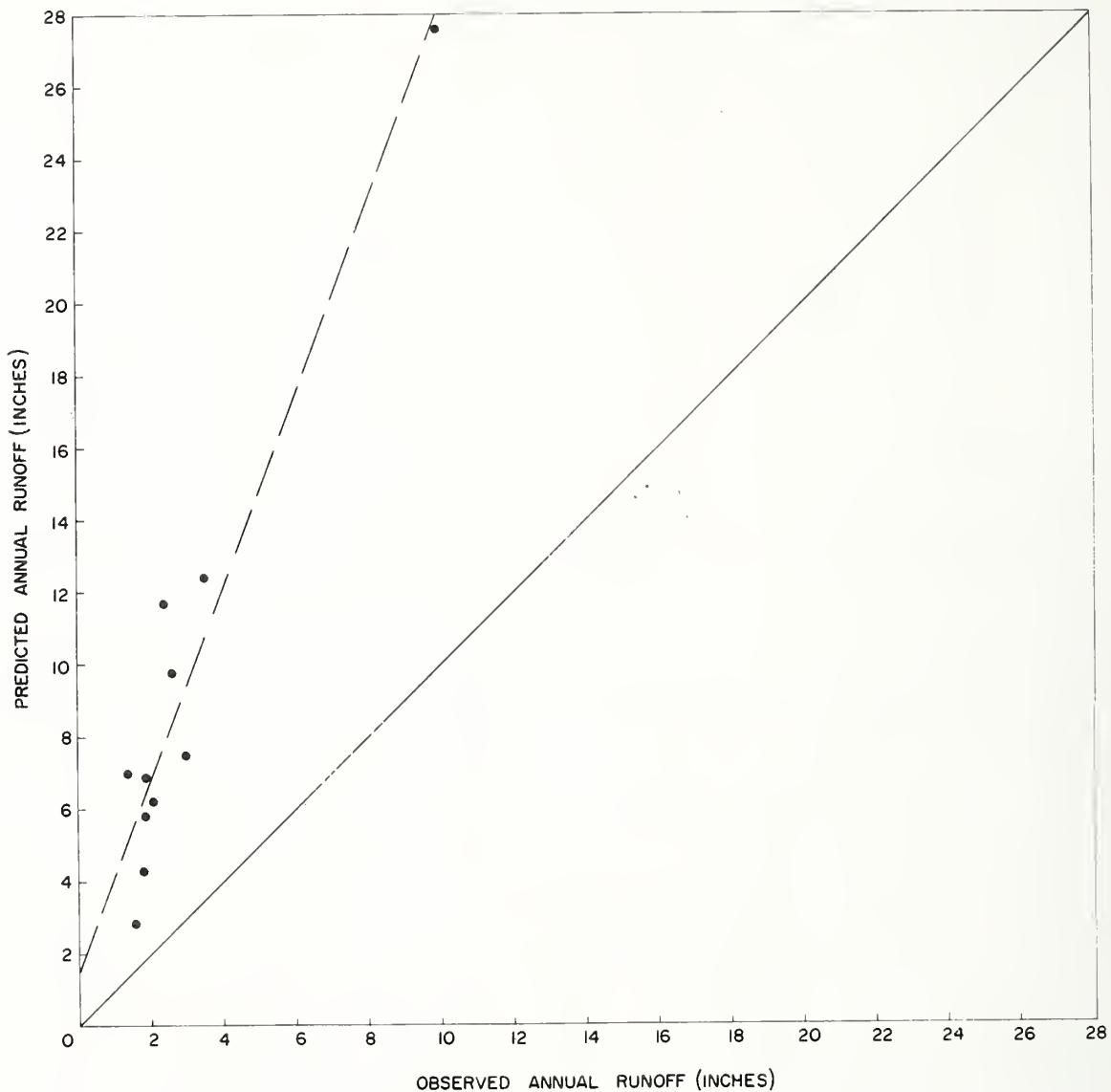


FIGURE 14-7.—Plot of predicted annual runoff against observed annual runoff for East Bitter Creek watershed.

wilting point. Part of the discrepancy between the observed and predicted soil moisture may have been the result of the rainfall input. Summer storms in the Southern Great Plains are very local. It is quite possible on watersheds the size of East Bitter Creek for a storm to produce 10 times more rainfall on one part of the watershed than on another.

We anticipated that the larger watersheds would be much more difficult to model. The larger number of soil and land uses did create problems in estimating the input parameters. Mean values

of the parameters had to be calculated by weighing according to the relative area of the soil or land use. Also, the use of a single rain gage to represent a spatially variable rainfall pattern was anticipated to cause larger errors on the larger watersheds. However, the preliminary results (table 14-5) did not indicate that larger watersheds with a greater number of soils and land uses cause larger errors or influence a trend to either overestimation or underestimation. The reason why the magnitude of all the overestimates was greater than that of the under-

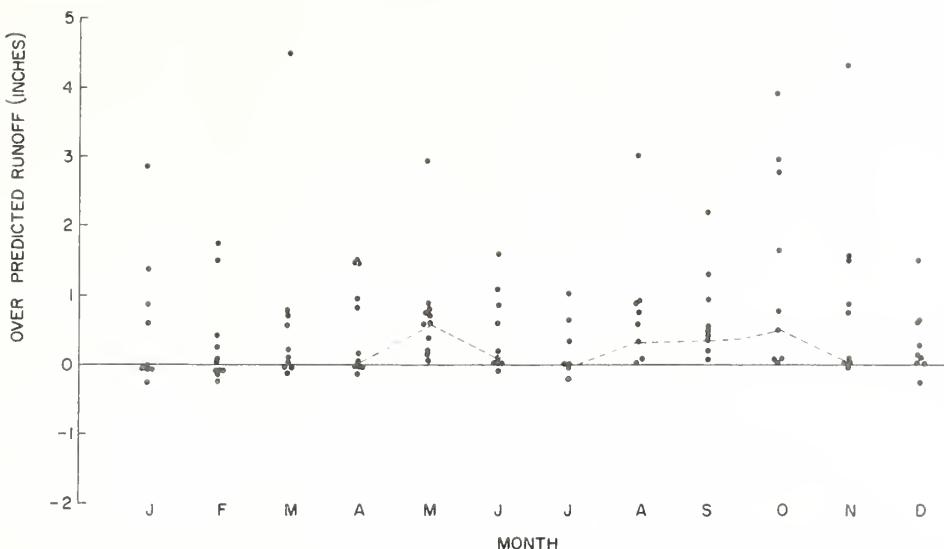


FIGURE 14-8.—Plot showing differences between predicted and observed monthly runoff values as a function of season for East Bitter Creek watershed.

estimates is not known. Preliminary analysis indicates that overestimates occur in wet years and underestimates in dry years.

Studies are currently underway to determine which input parameters require the greatest care in estimation. Since there are numerous parameters that could be tested, the evaluation must proceed in a systematic manner. For example, the shape of the hydrograph (fig. 14-5) indicates that the routing parameters were probably adequate. The error in peak flow indicates that the calculation of rainfall excess may have been in error. The usual sensitivity analysis, where each parameter is increased and decreased, was not appropriate because of computer costs.

One useful analysis technique is to plot predicted runoff against observed runoff, as illustrated in figure 14-7 for the annual values from East Bitter Creek. The data lie above and at an angle to the 1 to 1 line, indicating bias of overstorage in the model to account for the numerous farm ponds and reservoirs in this watershed. The small variation from a straight line reflects the high coefficient of determination, 0.91.

Another analysis technique is to plot the difference between predicted and observed runoff values as a function of the season of the year, as illustrated in figure 14-8 with monthly values from East Bitter Creek. The dotted line indicates

the median (50 percentile) values for each month. Note that overprediction is more frequent and larger than underprediction. The slightly more frequent overpredictions in the spring and fall correspond to the higher rainfall and runoff months of the year.

We found that the overland flow length required as a parameter for each zone was not a measurable parameter. Furthermore, when measurements were made the values used caused problems in getting the model to run at all. Usually, these values caused the computer storage to be exceeded when computing the subsurface flow. This situation was remedied by directly calculating overland flow length with a relationship present in the model for use when direct measurements are unavailable. The equation is

$$OVL = [(TP(2) \times FCAP(2) \times SOLID \times TOPD \times 0.01 \times f_c \times SL \\ \times AREA \times PCZON \times 43560.0 / C(1) - GR]^{0.5},$$

where OVL is the overland flow length, TP is the total porosity, $FCAP$ is the field capacity, $SOLID$ is the soil depth, $TOPD$ is the top soil depth, f_c is the infiltration rate at equilibrium flow, SL is the slope in feet per feet, $AREA$ is the watershed area, $PCZON$ is the percentage of watershed in this zone area, $C(1)$ is the maximum downward

movement of water, and GR is the ground-water recharge rate in inches per hour.

We also used breakpoint rainfall as input to small watersheds R-5, R-7, and C-4. These breakpoints, when used with the initial parameter estimates, increased the calculated runoff amounts from 10 to 54 percent, depending on whether there was wet- or dry-year rainfall. It is not known why these results were obtained or what part of the model was affected by the time scale input of rainfall.

As mentioned previously, the effects of farm ponds and flood-control structures were not investigated; however, their effect would influence the parameters of the model if calibration of these parameters were made without modification of the model. A structure routine based on a varying-area control by structure would be the easiest modification that could be made.

The cost of running the USDAHL model was compared with other similar models that do continuous simulation of flow. The Nonpoint Pollution Source (NPS) model (Donigian and Crawford 1976) and the Agricultural Runoff Management (ARM) model (Donigian et al. 1977) developed for the Environmental Protection Agency (EPA) were compared with the USDAHL model on watershed C-4. Costs of running the models for 1 year were \$4.38, \$23.31, and \$35.08 for the USDAHL, NPS, and ARM, respectively. Thus, the USDAHL model appears to be more efficient computationally than the two other models.

The USDAHL hydrologic model was used to simulate runoff from 12 watersheds in Oklahoma. The watersheds ranged in size from 13 acres to 182 square miles and contained various combinations of soils and land uses. Methods used to calculate the input parameters without optimization were described and discussed. The model was used as if the watersheds were ungaged. It underpredicted the monthly and yearly water yields on six watersheds by 5 to 55 percent, and it overpredicted on the other six watersheds by 190 to 390 percent.

Recommendations and conclusions.—We feel that the USDAHL model has potential as an operational tool in watershed planning and evaluation. We recognize that this model represents a state of the art in model development that is still in the experimental stages. We conclude on the basis of our evaluation that:

1. The model could be adapted to large watersheds with modifications.

2. The parameters necessary for modeling can be estimated from data that are being compiled by SCS field personnel and from data already on file.
3. With accurate parameter estimation, reasonable model prediction might be expected on both large and small (less than 10-square-mile drainage area) watersheds.
4. The model is cheaper to use than other models now available that do continuous flow simulations.

Based on results obtained with this model, we recommend that:

1. Modification be made to allow structural storage and depletion to be accounted for by the model. (The present model does not have this provision, which we feel is necessary for large watershed application.)
2. A channel-routing routine be added for large watersheds (greater than 10-square miles).
3. Modification be made to allow for separate rainfall inputs for each watershed zone or for adjustment of rainfall input based on location of station relative to each zone, and further study be made of the effects of input from time scale of rainfall on model results.
4. Model parameters be calculated from the data files now available to SCS. (As previously stated, programs for calculating land-use and soil parameters from the MIADS file have been developed; these procedures reduce the time in estimating parameters by more than one-half.)

CHICKASHA HYDROLOGIC TRANSPORT MODEL

The need for a simple field-size hydrologic transport model for a specific soil cover complex was identified during the early evaluation effort on more complex watershed models at the Southern Great Plains Research Watershed. A model was needed that would predict total storm or daily flows, peak hydrograph discharges, sediment loads, and total loads of nutrient from field-size or smaller agricultural watersheds. Existing models were costly to run and required large computer facilities and special data inputs.

The model described herein was designed to be simplistic, using state-of-the-art technology and

available data that would be at the disposal of research personnel as well as planning and operational staff personnel (Frere 1978). It runs on a small or miniature computer, does not require optimization of parameters, and is modular in construction so that submodels may be replaced or omitted, depending upon the user's needs. The model is considered to be a developmental tool from which improved research and operational models may be constructed. It provides a ready look at the effects of changing management practices and treatments without undue concern about absolute accuracy of output values. The model is not intended to be the final solution to pollution modeling, but it should provide the user with the framework of a model to which his own ideas may be easily attached.

Hydrology.—The basis for computation of direct flow is the SCS runoff curve number. The curve-number method, as described and used by SCS (U.S. Soil Conservation Service 1969), is for a single-event direct runoff from storm rainfall and antecedent moisture conditions. This method has been well tested on over 7,000 watersheds in the United States and in other parts of the world. In this model the basic runoff equation is

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}, \quad (1)$$

where Q is the direct storm runoff, P is the storm rainfall, and S is the initial abstraction.

The value of S is related to curve number and antecedent condition, thus

$$S = \frac{1,000}{CN} - 10, \quad (2)$$

where CN is the curve number for one of three moisture conditions (I, II, or III) based on levels of rainfall received in the previous 5 days before the runoff event. CN may vary continuously with changing soil moisture and ground cover.

To make this method continuous, the values of S for maximum and minimum retention (conditions I and III in dormant and growing seasons) are selected to give a soil-moisture storage reservoir in the upper profile. These values are related to curve number by hydrologic grouping of soil series, conservation practice, and cover complex or crop. The depletion of the soil-moisture storage between rainfall and runoff events is accomplished by calculating potential evapotranspira-

tion using the Jensen-Haise model (Jensen and Haise 1966), which is given as

$$ET = (0.14T - 0.37)RS, \quad (3)$$

where ET is the daily potential evapotranspiration, T is the mean daily air temperature ($^{\circ}$ F), and RS is the daily total solar radiation in evaporation equivalent units (inches).

Potential evapotranspiration is assumed to be equivalent to actual evapotranspiration when the soil moisture is between field-capacity and wilting-point levels and is reduced by a multiplicative value of 0.0082 when the moisture level approaches wilting point.

At this point in the model development, continuous direct runoff computation can be accomplished by using daily or storm rainfall, daily air temperature, and solar radiation. All of these values are available from the National Weather Service. At least one hourly or daily rainfall station is located in each county of the midwestern and eastern sections of the United States. Most climatic stations record air temperature. Solar radiation data were available at one location in each State until 1978, and these values can now be estimated from sky-cover and percentage-of-sunshine data that are published for first-order weather stations.

Peak flows are often needed in design and in sediment-transport estimation. The Chickasha model uses the SCS method to estimate peak flow. This equation, given in the National Engineering Handbook (U.S. Soil Conservation Service 1969), is

$$L = \frac{l^{0.8}(S+l)^{0.7}}{1,900Y^{0.5}} \quad (4)$$

where L is the lag, l is the hydraulic length of the watershed, S is the retention from CN (curve number), and Y is the average watershed slope.

Thus, the peak flow, Q_p , is calculated by

$$Q_p = \frac{484AQ}{\frac{\Delta D}{2} + L}, \quad (5)$$

where A is the watershed area, Q is the total storm flow, $\Delta D = 1.33T_c$ (time of concentration), and L is the lag = $0.06T_c$.

Sediment transport.—The method of sediment-transport estimation used is a modification of the

Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) developed by Williams (Williams and Berndt 1975). This method relies on a runoff factor instead of the rainfall factor in USLE. Peak flow and total storm flow are required as given by

$$SED = 95.0(Q_p \times Q)^{0.56} K \times L \times S \times C \times P, \quad (6)$$

where *SED* is the storm sediment load in tons, Q_p is the peak storm discharge, Q is the storm volume, K is the soil erodibility, L is the length, S is the slope, C is the cover factor, and P is the practice factor for a field or watershed. Guidelines for selecting parameter values are given by Wischmeier and Smith (1978). The exponent value 0.56 has been fitted by Williams (Williams 1975) for several locations in the United States and does not vary significantly.

Chemical transport.—The model was developed to use available data and parameters that could be estimated by the user. The loading-function models for nutrients were added to the model for chemical transport. The models for nitrogen and phosphorus were first approximations for which loading-function and enrichment-factor estimates could be made from data given by McElroy et al. (1976).

The model for nitrogen is given as

$$YNAE = 20.0 \times SED \times CSNT \times RN \times FN,$$

where *YNAE* is the nitrogen load on sediments, *SED* is the sediment load, *CSNT* is the total nitrogen concentration in the soil, *RN* is the nitrogen enrichment ratio, and *FN* is the nitrogen loading function.

Total nitrogen coming to the land surface in rainfall is calculated by

$$YNPR = AREA \times (Q/QPR) \times XPR \times BC,$$

where *YNPR* is the rainfall nitrogen from runoff, Q is the total direct storm runoff, QPR is the storm rainfall, *XPR* is the nitrogen load in precipitation, and *BC* is the precipitation alteration factor.

Total nitrogen load from a storm, *YNA*, is calculated by

$$YNA = YNAE + YNPR.$$

Total phosphorus load for a storm is calculated by

$$YPT = 20.0 \times SED \times CSPT \times RP \times FP,$$

where *YPT* is the phosphorus load, *SED* is the sediment load, *CSPT* is the total phosphorus load in the soil, *RP* is the phosphorus concentration in the soil, and *FP* is the phosphorus loading function.

Model input.—The model requires input of at least daily rainfall. However, in its present form hourly rainfall is entered and summed to daily values. Storm or daily amounts could be entered just as easily by changing or deleting subroutine RAINL and adding the appropriate coding for the rainfall input desired. All values of rainfall for each rain-day are entered and stored in an array of 365 values (zeros for nonrain days).

Daily minimum and maximum air-temperature and solar-radiation values are entered for each day of the year. This routine is now coded implicitly within the main program; however, it could be easily modified.

Model parameters.—The parameters required for direct runoff calculation are *CN*, the curve number for moisture condition I, II or III from tables given in the National Engineering Handbook (U.S. Soil Conservation Service 1969) for a given soil cover complex, and *XAMC*, the starting moisture level. The beginning and ending date of the growing season is entered for informational purposes, as well as the antecedent moisture level from 5-day rainfall totals as given in the National Engineering Handbook for both growing and dormant seasons. Identifying information for the type of crop, moisture condition, code, and hydrologic soil group are required but are not used as parameters.

The peak-flow and sediment-load parameters are entered together because they are used in the same subroutine. These are *AREA*, area of watershed; *HL*, maximum hydraulic length of flow; *YS*, average watershed slope; *XK*, erodibility factor; *XLS*, length-of-slope factor; *XC*, cover factor; and *XP*, practice factor. *AREA*, *HL*, and *YS* can be obtained from watershed topographic maps, and *XK*, *XLS*, *XC*, and *XP* from Agriculture Handbook 537 (Wischmeier and Smith 1978).

The chemical transport parameters required by the model can be obtained from McElroy et al. (1976). The values are generally given in the form of maps and, in some cases, by suggested values.

Table 14-6.—Observed and predicted values for the Chickasha hydrologic transport model for each of four watersheds in study

Statistical parameter	C-4	C-5	R-5	R-7
RUNOFF (INCHES)				
Years of record	8.0	8.0	8.0	8.0
Rainfall	27.58	27.58	29.51	30.27
Observed runoff	3.40	2.24	1.80	5.98
Standard deviation	2.18	2.21	2.25	3.56
Predicted runoff	3.23	2.43	2.00	5.75
Standard deviation	2.33	1.92	1.30	3.12
SEDIMENT TRANSPORT (TONS/ACRE/YEAR)				
Years of record	8.0	8.0	8.0	8.0
Observed sediment	1.47	.50	.03	2.5
Predicted sediment . . . . .	.65	1.44	.15	4.03
TOTAL NITROGEN IN RUNOFF (LB/ACRE)				
Observed total N	0.260	0.149	0.060	0.211
Predicted total N . . . . .	.231	.304	.067	.221
TOTAL PHOSPHORUS IN RUNOFF (LB/ACRE)				
Observed total P	0.201	0.077	0.034	0.083
Predicted total P . . . . .	.193	.246	.035	.044

¹Values are averaged for the period October 1972 to December 1974.

Model output.—The model will generate header information containing watershed identification, area, hydrologic condition, listing of input parameters, and other information such as number of years, etc.

The next output is a table containing the date, rainfall amount, runoff, peak flow, lag time, sediment load, nitrogen loading from sediment, nitrogen loading from rainfall, total nitrogen load, and total phosphorus load. Only dates on which runoff has occurred are included in the table. A summary of total monthly and annual values are listed next, followed by a summary of the event distribution during the year.

At the end of the run, after all years of input record have been processed, a statistical summary is listed giving the means of standard deviations and coefficients of determination of observed and predicted flows.

The model is coded in FORTRAN IV and can be run on an 8K IBM 1130 computer when the statistical summary is omitted. The present version is coded for a 32K NOVA minicomputer. The model has also been run on remote batch to an IBM 370-168 computer.

The model is not a finished product but is intended to be used as a developmental tool for transport-modeling investigation. The various components of the model runoff, evapotranspiration peak flow, sediment loading, and nutrient transport may be revised or changed according to research findings and new developments.

Examples of outputs and comparisons with observed data (table 14-6) show that the model is useful in estimating trends from field-size areas where little data exist on chemical transport.

OTHER MODELS TO BE TESTED

Several types of hydrologic and hydrologic transport models have been obtained, converted, and compiled to run on the computer system in use at Chickasha. These models will be tested using the hydrologic sediment-erosion and chemical data bases compiled for small and large watersheds. Several of these are basin-size models that deal with lumping of parameters, similar to the USDAHL

model. Others are strictly field-size or small watershed models that require detailed inputs and parameter estimates. Some are event models that produce output for a single hydrologic event, and others, especially those of field-scale size, are continuous simulation models that simulate hydrologic conditions from event to event.

The basin models, which will be tested on an event basis, are Hydrologic Engineering Center (HEC) models HEC-1, HEC-2, and HEC-6. These models were developed by the U.S. Army Corps of Engineers (1973a, 1973b, 1977). Another event type model that will be tested is the Storm Water Management Model (SWMM) model developed for EPA.

Field-scale models to be tested are the previously mentioned ARM and NPS models developed for EPA. Early versions of these models have been run using the cropland and rangeland watershed data summarized in table 14-6. The Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model developed by ARS will also be tested using these same data (Knisel 1978).

SUMMARY

The USDAHL model and a simple field-scale model for simulating hydrologic sediment and chemical transport were tested at Chickasha, Okla. Limitations of the models and the modifications required to apply them to the watersheds in the Great Plains were identified. The results of these studies will be used to develop improved models for simulating hydrologic transport for watersheds in this region.

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Section 15.—Instrument Development and Testing

INTRODUCTION

Careful attention to detail, extra effort, and regular preventive maintenance are helpful in obtaining accurate records, and a need for highly accurate hydrologic records was recognized at the beginning of this research project. However, as the project developed, the need became apparent for certain specialized items of equipment that were not commercially available. This section discusses the development of water-level measuring devices and the Chickasha sediment sampler. The findings from studies of the performance of other items of equipment are also included.

WATER-LEVEL MEASUREMENT

Siphon method.—Continuous records of the water level were needed at an existing reservoir where water was impounded behind an earthfill dam. None of the various conventional methods of measuring water levels seemed feasible for use at this site. To meet the requirements of simplicity and structural safety, a siphon method was developed and successfully used (Yost and Naney 1969).

The siphon maintains the water level in the small-diameter well at the same elevation as the reservoir surface; the system acts as a siphon-operated manometer. Indirect measurements of the reservoir level can thus be made by measuring the water level in the well. The measurements are recorded continuously by a conventional recorder. The siphon action is easily started by use of a special primer. An air trap and a sediment sump prevent stoppage of the siphon line by either air or sediment.

The characteristics that particularly contribute to the usefulness of the siphon method are its ac-

curacy and the fact that its installation, maintenance, and operation are simple and economical. Installation requires neither great skill nor complex tools, and materials are inexpensive and readily available.

Cantilevered wire-weight gage.—A cantilevered wire-weight gage (Edens et al. 1966) was devised to obtain a direct reading of the surface water level in a stream where the installation of a staff gage is not feasible. Staff gages are often difficult to read, catch debris, and may be lifted by ice formation or washed away during floods. An experimental gage (fig. 15-1) was used for 15 years at the West Bitter Creek gaging station.

The weight, a 1-inch (i.d.) pipe filled with lead, is sufficient in size to prevent slack in the tape. With the weight in the "up" position, nearly all of the tape is wound on the reel, which is enclosed in a metal box at the back of the boom. The pipe in the center of the boom encloses the tape and also provides a reference point for reading the tape. The remainder of the line, extending from the tape end to the weight, is lightweight aircraft cable. This cable is less subject to wind resistance and fluttering than a tape; thus, more accurate water-level readings can be obtained with the cable.

A gun-sight system is included to facilitate checking the alignment of the gage, which can be aligned by adjusting one or more of three turnbuckles. A small chain (not shown in figure 15-1) is looped through the turnbuckles and padlocked to prevent unauthorized adjustments.

Giant sand point.—At gaging sites with bubble-gage water-level manometers, an orifice housing (Hunt et al. 1966) was devised to prevent orifice plugging by shifting sand-bed deposits. The housing, a giant sand point, was designed to provide firm anchorage independent of any other supporting structure, ample storage for silt, exclusion of sediment, and sensitivity to the water

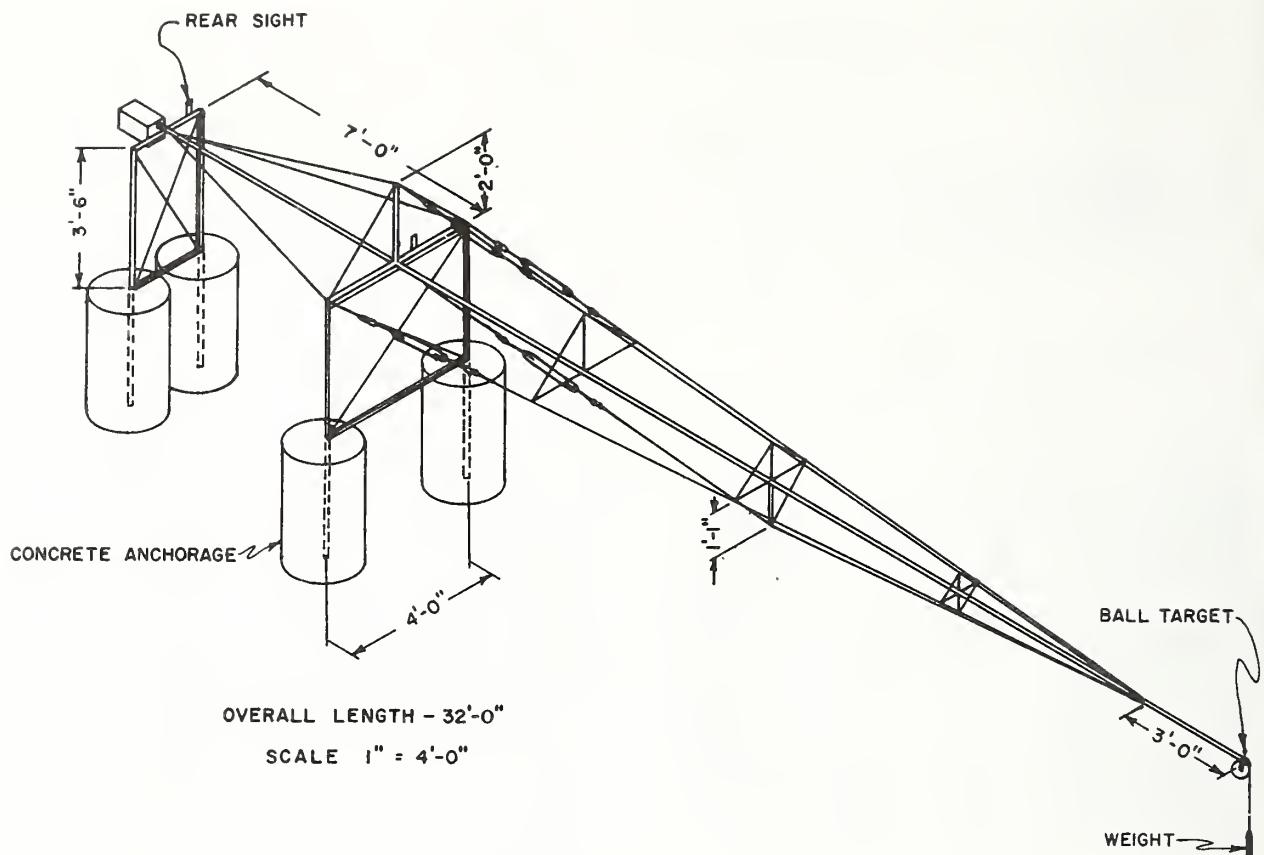


FIGURE 15-1.—Self-supporting wire-weight gage.

level. Also, a self-cleaning sand point was designed for attachment to a bridge pier.

The giant sand point is a 4-inch (i.d.), standard-weight, galvanized pipe about 20 feet long with a bubble-gage orifice installed in its side near the top. A vented cap is provided to minimize sediment entry into the pipe and yet permit escape of nitrogen gas from the bubble gage, thus preventing pressure build-up inside the pipe. Sensitivity of water level in the pipe to water level in the stream is provided by a series of lengthwise slots in the pipe. The slots are covered with screen wire to hinder sediment entry.

A self-cleaning sand point, requiring little maintenance, was developed for use where the following conditions could be met: (1) an available structure, such as a bridge, pier, or piling, to which the sand point can be securely attached and (2) the occurrence of considerable scouring of the channel during a runoff event. Scouring of the streambed below the open bottom of the sand point is essential for self-cleaning. The self-

cleaning sand point is similar to the giant sand point except for a more simple vent cap and a shorter pipe.

Low-water training fences.—The constant meandering of a low-flow channel within the main channel of a sand-bottom stream had posed a problem in locating the orifice of a bubble-gage water-level recorder. The problem was solved by installing low-flow training fences (Hunt and Goss 1970) to direct and position the low flow at any desired point in the streambed. Thus, the training fences allow the bubble-gage orifice to be located at a fixed position and improve the accuracy of discharge records by reducing and stabilizing the width of the low-flow channel. Training fences also keep low and intermediate flows at the right approach to weirs.

The training fence is a series of angle-iron posts set in a line about 4 feet apart and hydraulically jetted 12 to 14 feet into the streambed. The tops are 0.5 to 1 foot above the water surface at mean low flow. Two strands of No. 9 galvanized wire,

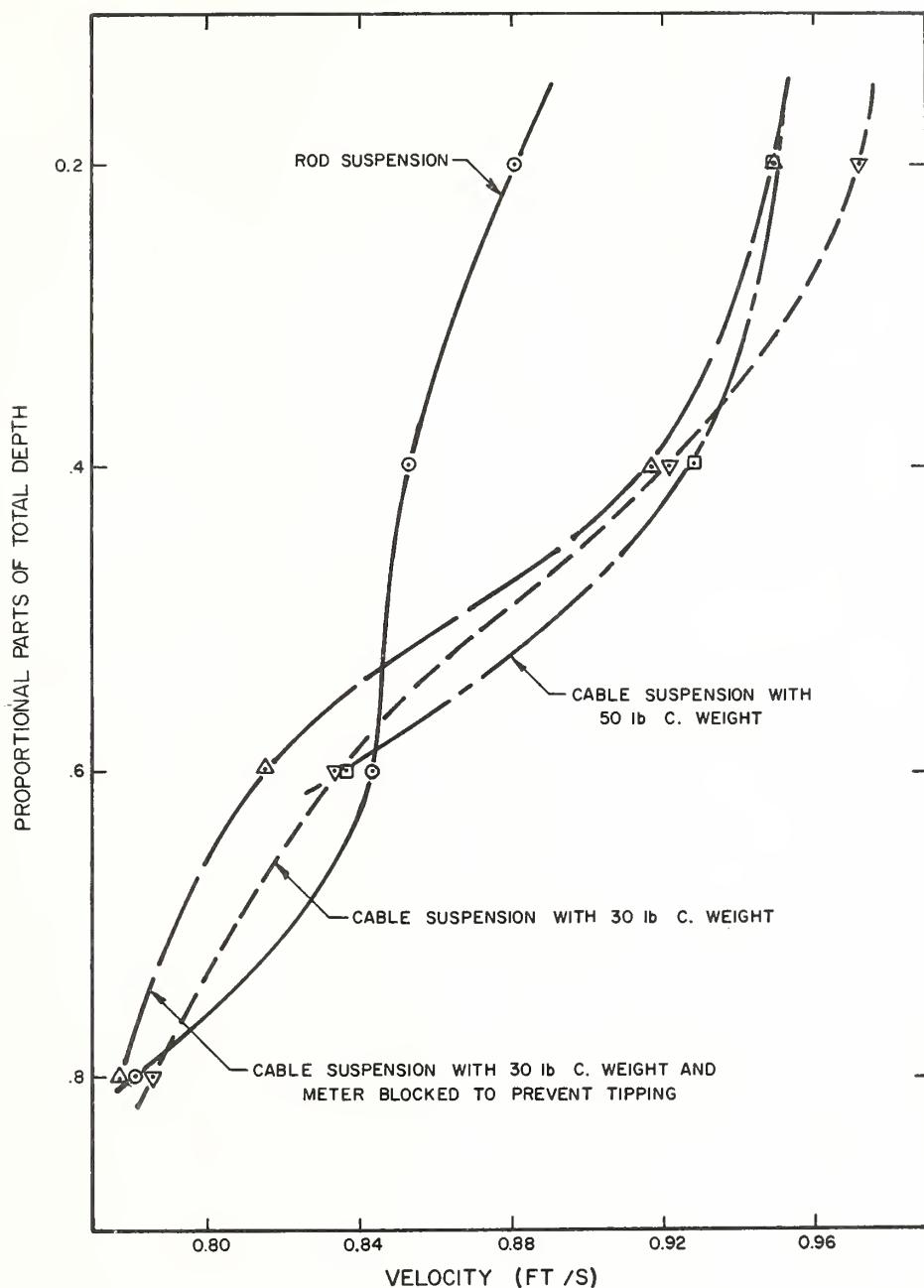


FIGURE 15-2.—Effects of current-meter suspension methods on a vertical velocity profile in the Washita River.

placed 1 foot apart, are stretched along the upstream face of the fence and fastened securely to it, with the top wire at the top of the angle-iron posts. One-inch-mesh chicken wire, 1.5 feet high, is stretched along the upstream face of the fence and fastened securely to the angle-iron posts and the No. 9 galvanized wires. Angle-iron ribs are

then fastened horizontally across the upstream face near the top of the fence to protect the chicken wire from logs and other debris. Generally, streams that occasionally have high velocities (7 to 11 feet per second) require one or two backup fences set 5 to 10 feet downstream and parallel to the major fences.

CURRENT-METER MEASUREMENT

Accuracy of measurements.—Early in the Washita research project, a study was made of the accuracy of the Price current meter (Schoof 1965, Schoof and Crow 1968a, 1968b). Current meters had always been rated in a laboratory by towing the meter through still water. The rating tables for the Price meter were made to apply when measurements were made with the meter on a cable suspension. The laboratory ratings indicated that the tabular velocities should be reduced by 2 percent for measurements made with the meter suspended on a wading rod.

A series of tests was conducted on the Washita River using both cable and rod meter suspension at a flow depth of 2 to 3 feet. At 0.6 and 0.8 of the total depth, there was no significant difference between velocities registered by either meter (fig. 15-2). However, at 0.2 and 0.4 of the total depth, the cable-suspended meter registered about 9 percent greater velocity than did the rod-suspended meter. Under field conditions, rod-suspension measurements yielded estimates of discharge that were about 4.3 percent lower than estimates from cable-suspension measurements when the same rating table was used for each. The reason for the difference appeared to be the presence of a stream gager in the water near the rod-suspension meter during the field operation.

For many years, new current meters have generally not been individually rated. When a new meter is purchased, a standard rating for that type of meter is provided. However, individual ratings of a few meters have been made and were found to be well within 2 percent of the standard rating, which appeared to be of satisfactory accuracy.

Measuring rapidly changing flow.—A technique for obtaining accurate flow measurements in rapidly rising and falling streams was discussed by Blanchard and DeCoursey (1968). The technique prescribes measuring velocity at alternate stations across a stream and at intermediate stations on the return trip. This routine is repeated until the flow has receded. The times of individual measurements are recorded, and an adequate number of water-level measurements are made to ensure a valid stage record.

From these data, stage-velocity and stage-depth curves are plotted for each stream-width increment. Velocities and depths obtained from

these curves are used to calculate a stage-discharge relation at each station. A summation of discharges for all stations at a given stage is the discharge of the stream at that stage. A series of summations at various stages on the rise and recession will provide the data necessary to construct a composite stage-discharge curve. This technique offers an opportunity to obtain measurements of rapidly changing streamflows, regardless of the rate of change in stage. The detection of velocity and depth errors is an added advantage of this technique.

V-NOTCH WEIRS

Accurate measurement of discharge was considered to be essential in the research project because some of the changes in streamflow resulting from conservation treatment might be small and difficult to detect; therefore, several V-notch weirs were installed. Blanchard and DeCoursey (1970) discussed the techniques used in the design of these low-flow controls at gaging stations in drainage areas of up to 60 square miles.

Blanchard (1966) developed a design formula for these weirs as follows:

$$\frac{Q_p}{Q_l} = \left[1 - \left(\frac{H_2}{H_1} \right)^{2.80} \right]^{0.385}$$

where Q_p is the discharge in cubic feet per second predicted by the Villemonte relationship; Q_l is the discharge in cubic feet per second calculated by the free-fall equation, $Q_l = 6.75H^{2.80}$; Q_p/Q_l is the flow reduction due to submergence; and H_2/H_1 is the submergence ratio.

A significant conclusion from this work is that a controlled area should be incorporated in the design of a weir. Thus, there should be a stabilized channel lining extending some distance upstream from the weir.

DeCoursey and Blanchard (1970) discussed the flow analysis of large triangular weirs. Two equations were derived—one assumed that a continuous record of the average velocity of approach was available, and the other used the rate of change in stage to approximate the effects of unsteady flow situations on weir flow and did not require a velocity. These equations were derived by theoretical analysis of a set of field measure-

ments and were then simplified as much as possible. The equations thus derived were more accurate than conventional weir-flow equations. Results of the experiment show that (1) if the weir rating is based upon both the static and velocity heads, the effect of submergence is one of a superposition of flows and (2) the rate of change in stage does not fully define unsteady flow.

CHICKASHA SEDIMENT SAMPLER

Early in the watershed research project the need was recognized for an automatic small-capacity, pumping-type sediment sampler for intermediate- and small-size watersheds that would be less expensive and simpler than the samplers that were then available. Since no such sampler existed, one was designed and built at Chickasha (Allen et al. 1976). The sampler, shown in figure 15-3, was patterned after an experimental sampler developed by the Federal Inter-Agency Sedimentation Project (1962). It is a stand-alone unit with a rotating tray that will hold 28 pint bottles and is powered by a 12-volt automotive battery.

Although various devices have been developed to turn the sampler on, the most common method consists of a weighted, plastic fishing float suspended by a line from the arm of a snap switch, all mounted within the stage-recorder stilling well. A stream rise buoys the float and actuates the switch, which sends power to a small motor coupled to a gear reduction unit. (Older versions used an electric clock.) A notched sampling-frequency wheel is secured to the output shaft of the gear reduction unit. As the wheel rotates, the arm of the sampling-frequency switch falls successively into the notches. (An alternate method uses a light source, a rotary disk with pin holes, and photocells to control sampling frequency—one for the rising stage and another for the falling stage.) The sampling-frequency switch activates a timer with four adjustable cam switches. These four switches, each in sequence, advance the tray to a fresh bottle, turn the pump on, actuate a flow diverter to fill a sample bottle near the end of the pumping cycle, and stop the timer until rotation of the sampling-frequency wheel starts the cycle anew. The sampler is cut off when all 28 bottles are filled or when the stream drops below the stage that actuates the float switch.

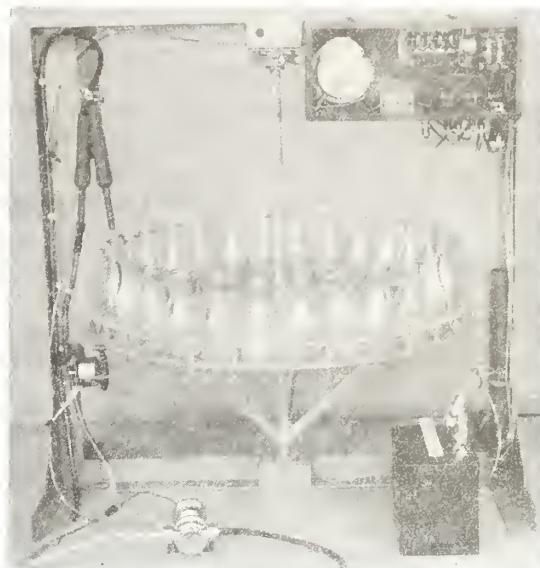


FIGURE 15-3.—Chickasha sediment sampler.

The concentration of samples collected with the pumping sampler from a point in the stream were compared with manually collected equal-transit-rate samples representing cross-sectional concentrations (Welch et al. 1971). There was a good relationship between sample concentrations when most of the sediment in suspension was silt and clay. However, the correlation decreased as the amount of sand in suspension increased and made it difficult to locate a sampling point that was representative of cross-sectional concentrations.

In 1979, about 70 of these samplers were being used for watershed research, primarily by Agricultural Research Service. They are available from the Federal Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minn. The 1979 price was approximately \$1,600 f.o.b., Minneapolis.

LIGHT-ACTIVATED SIGNAL GENERATOR

This signal generator was designed to activate a sediment sampler at intervals controlled by the stream response. The sampler can sample at different intervals for the rise and fall of flow, both of which are controlled by the elevation of the water in the stream.

The activator device consists of light-sensitive transistors (Edens and DeCoursey 1975). A disk

with three circular rows of holes one-quarter of an inch (6 millimeters) in diameter is mounted on the shaft of the water-level recorder. The light-sensitive transistors pick up light through the holes as the disk rotates and thus control the action of the sampler. This inexpensive device is an improvement over other available stage-activated systems and can be adjusted to anticipated watershed conditions on streams of all sizes.

MEASURING SUSPENDED-SEDIMENT CONCENTRATIONS

Watershed research studies on erosion, sediment yield, and transport of those chemicals adsorbed to sediments involves the collection and analysis of sediment in a large number of suspended-sediment samples. Much effort has been expended to develop instruments that will automatically measure sediment concentrations in streams and thus replace the slower and costlier conventional procedure. So far, none of these instruments have been successful enough to warrant their widespread use.

Turbidimeter.—From 1968 through 1970, Allen (1979) tested a turbidimeter in the field and laboratory to determine its feasibility for use in watersheds of the Southern Great Plains. Its accuracy in measuring suspended-sediment concentrations was not good. Maximum errors were 184 percent at one gaging station and 261 percent at another, with average errors of 31 and 25 percent. Further research to find the cause of the poor prediction showed that the turbidimeter was far less responsive to sediment with large particles than to that with smaller particles. In suspended sediments containing fine particles, the turbidimeter could hardly detect large concentration changes in coarse sediment fractions.

A fairly good relation was found between turbidity and concentration of finer sediment sizes (less than about 0.010 millimeter). This finding suggests that turbidimeters may have use in cases involving fine sediments, such as (1) determining total load where the transport is predominately fine material, (2) determining sediment concentrations where only the fine material is desired, or (3) measuring concentrations for reservoir research where only the fine material reaches the main body of water (Allen 1979).

Nuclear sediment gage.—The nuclear sediment gage was tested by comparing sediment concentrations sensed by the gage with stream cross-sectional concentrations (Welch and Allen 1973). The correlation between the concentrations determined by the two methods was significant at the 1-percent level, with standard error of estimates ranging from ± 172 to 1,884 parts per million. Sediment concentrations predicted with the calibration curves developed were accurate enough for most applications and indicated the principle to be sound and feasible. Obstacles to routine use of the gage tested were the high cost of purchase and maintenance, low operational reliability, and low sensitivity to low concentrations.

PARTICLE-SIZE ANALYSIS

Since pollutants are often adsorbed on transported soil particles, there has been a need for particle-size information on water-borne material from field and watershed areas. The pipette has generally been accepted as the standard for particle-size analysis, but it is laborious, time consuming, and not well suited for analysis of suspended-sediment samples. Thus, a particle-size analyzer was tested as an alternate method (Welch et al. 1979).

The particle sizes indicated by the analyzer were compared with those of the pipette analyses. The two methods agreed within ± 5.5 percent on the 55 samples tested and were within ± 3.7 percent on 12 of the samples treated to remove organic matter and soluble salts. The particle-size analyzer required less time and labor for analysis and calculation of results but required approximately the same amount of time as the pipette for sample preparation.

SUMMARY

A siphon system for a gage well intake was installed at a reservoir. The installation, maintenance, and operation were simple and economical, and a desired level of accuracy was achieved. A cantilevered wire-weight gage, a giant sand point for the bubble-gage water-level recorder, and low-water training fences for directing low flow to the sand point all assisted greatly in improving the quality of the runoff records.

A study of the accuracy of current-meter measurements indicated that, for flow depths of 2 to 3 feet, rod-suspension measurements yielded estimates of discharge that were about 4.3 percent lower than estimates from cable-suspension measurements when the same rating table was used for each. The reason for the difference appeared to be the presence of the stream gager in the water near the rod-suspension meter during the field operation. A technique for obtaining accurate flow measurements in rapidly rising and falling streams was developed and applied successfully.

A significant conclusion from a study of weir design was that there should be a stabilized channel lining extending some distance upstream from a weir. The purpose of the lining is to stabilize fluctuations in the water level-discharge relation caused by scour and fill immediately upstream from the weir. An analysis of flow over large triangular weirs indicated that, if the weir rating is based on both the static and velocity heads, the effect of submergence is one of a superposition of flows and that the rate of change in stage does not fully define unsteady flow.

A small-capacity sediment sampler for intermediate- and small-size watersheds was developed and has become known as the Chickasha sediment sampler. For small watersheds, this sampler is simpler and less expensive than other available automatic pumping samplers. It holds 28 pint bottles and is powered by a 12-volt automotive battery. A light-activated signal generator was developed to activate the sampler. This device employs a light source, a rotary disk with pin holes, and photocells to control sampling frequency.

Field and laboratory tests were conducted on a turbidimeter, an instrument designed to automatically measure sediment concentrations in streams. Accuracy of the instrument was not good; the average errors at two stations were 31 and 25 percent. The turbidimeter was far less responsive to sediment with large particles than to that with small particles.

Tests of the accuracy of a nuclear sediment gage were much more favorable. The tests indicated that its accuracy was sufficient for most applications. However, the gage is expensive, has low operational reliability, and has low sensitivity to low concentrations.

Tests of a particle-size analyzer gave results that were within ± 5.5 percent of those of the pipette analyses on 55 samples. Use of the

particle-size analyzer saved time in analysis but not in sample preparation.

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Section 16.—Summary

CONCLUSIONS

1. The annual variation of rainfall was greater than expected, based on records from long-term climatic stations. Within the study reach there was an average variation of 14 inches in annual gage catch, with less than 29 miles between the gages recording the high and low amounts. These variations, often within a county area, are significant when compared to data used to forecast crop yields and production, which are generally based on one value of rainfall per county.
2. Eighteen years of rainfall data have provided the necessary stochastic characteristics required for generation of synthetic data that can be successfully used to extend the rainfall and climate inputs to hydrologic models.
3. Scaling of field-measured infiltration data was accomplished fairly successfully by use of the similar-media concept. In this study, scaling based on A of the Philip equation gave better results than scaling based on S . However, scaling was improved by using an average of α_S and α_A . The scaling factors were log-normally distributed.
4. A study of remotely sensed multispectral scanner (MSS) digital data showed that linear combinations of watershed values can repeatedly be related to the watershed-runoff coefficient (CN) used in the Soil Conservation Service (SCS) storm-runoff equation. The improvement possible in calculating CN can result in significant improvement in estimating the runoff necessary for the design of flood-control structures.
5. The difference in temperature while using the horizontal polarized passive microwave imaging scanner (PMIS) during two flights over the same watershed, when vegetation and antecedent moisture conditions were different, was related to the SCS watershed storm-runoff coefficient and could be used to develop a prediction scheme for such coefficients.
6. Measurement of suspended sediments in water using an MSS radiometer is feasible for concentrations of up to approximately 75 parts per million, depending on the color and source of the sediments. However, remote sensing of heavy concentrations of suspended sediments with visible or near-infrared light is not feasible and may produce misleading results.
7. Surface runoff from scrub-oak-timbered sandy land is insignificant, which should be considered in the design of impoundments.
8. Many watersheds do not show a significant reduction in water yield following treatment with floodwater-retarding structures. However, the structures may reduce the annual water yield of watersheds in the Southern Great Plains having drainage areas of less than 300 square miles by more than 25 percent when the average annual rainfall is less than 32 inches.
9. There was no apparent reduction in water yield from the 1,130-square-mile Washita study reach during the studies. Apparently, dredging of two tributaries, combined with removal of timber during the studies, increased the yield as much as structures controlling up to 34 percent of the area decreased it. Also, there has been no measurable reduction in water yield from the entire Washita River basin since installation of the structures.
10. On the average, the structures reduce peak flows from tributary watersheds by a percentage equal to the percentage of the drainage area controlled by the structures.
11. The Universal Soil Loss Equation multiplied by an estimated delivery ratio is probably suitable for ranking sediment-source areas but not for making sediment-yield estimates unless the estimates are needed only within several orders of magnitude. The Modified

Universal Soil Loss Equation appears better suited for sediment-yield estimates but requires either measured or estimated runoff data and may need to be calibrated with data from the watershed of interest.

12. Sediment-yield reductions from tributary watersheds treated with floodwater-retarding structures varied. For five watersheds, reductions ranged from 40 to 60 percent. For three watersheds, however, no reduction could be detected after treatment.
13. Small channels below structures generally aggraded during the studies. Some tributary channels changed from box shape to smaller V-shape, and trees became established on the banks in some reaches. Little change was detected in the Washita River channel. However, with time, a slightly smaller, narrower, deeper, and more stable channel is anticipated.
14. The model testing at Chickasha has pointed out the need for better models for basin-scale prediction of water, sediment, and chemical transport. Though existing models can be applied with reasonable results by trained personnel on small areas such as fields, these models are not adequate to predict or identify pollution sources from large basin-size areas having mixed land use and complex drainage channel networks. Models that will use the rainfall variability definition through multiple rainfall input must be developed. Soil, land-use, and other parametric data must be easily obtained and processed by computer to make use of the more complex basin model both viable and practical.
15. Soil- and ground-water salinity increase immediately below floodwater-retarding structures as a result of piezometric surfaces caused by seepage waters. Emerging seepage waters have mineral concentrations 4 to 6 times higher than parent lake waters. The seepage effects appear to be limited to less than 1,500 feet downstream from the structure.
16. Nutrient losses are generally low in runoff from cropland and rangeland in central Oklahoma. However, soluble nutrient concentrations, especially from fertilized areas, may contribute significantly to eutrophication of receiving waters.

SUGGESTIONS FOR FUTURE STUDY

1. The rain-gage network in the Southern Great Plains Research Watershed is the largest of its type in the world. With 18 years of continuing records over a 1,400-square-mile area, the importance of the network to hydrologic modeling and future studies with remote sensing is incalculable. The network can support many interdisciplinary studies related to water-resource planning, crop production, and economic prediction based on climatic experience. Thus, this research should be continued to support such studies, which are now being planned.
2. Surface-water and sediment yield from the densely timbered upland areas in this region are insignificant. However, the hydrologic effect of timber removal and conversion to grass or cropland is unknown. This effect could be determined by removing the timber from a previously studied watershed and then obtaining additional records. Runoff- and sediment-yield data are also needed from upland cropped areas to aid in model development.
3. Pretreatment water-temperature records were collected at four gaging stations in the 1960's. Posttreatment temperature records should be obtained to determine if the structural treatment has affected the water temperature of the stream.
4. A small amount of data on soil erosion from a road indicates that erosion from roadways contributes significantly to the sediment content of streams in this area. There is a need to determine the best management practices for reduction of erosion from roads. There is also a need to expand research on the treatment of gullies.
5. The effects of the flood-abatement program on channels may be long term. Therefore, a resurvey of channel cross sections should be made in 1990 and 2000 to determine relative channel changes in treated-versus-untreated watersheds.
6. The need exists to define and quantify the relationships among cover, soil-water characteristics, and existing moisture conditions and also the relationship between water infiltration and its return to channel flow. A better understanding of subsurface water movement

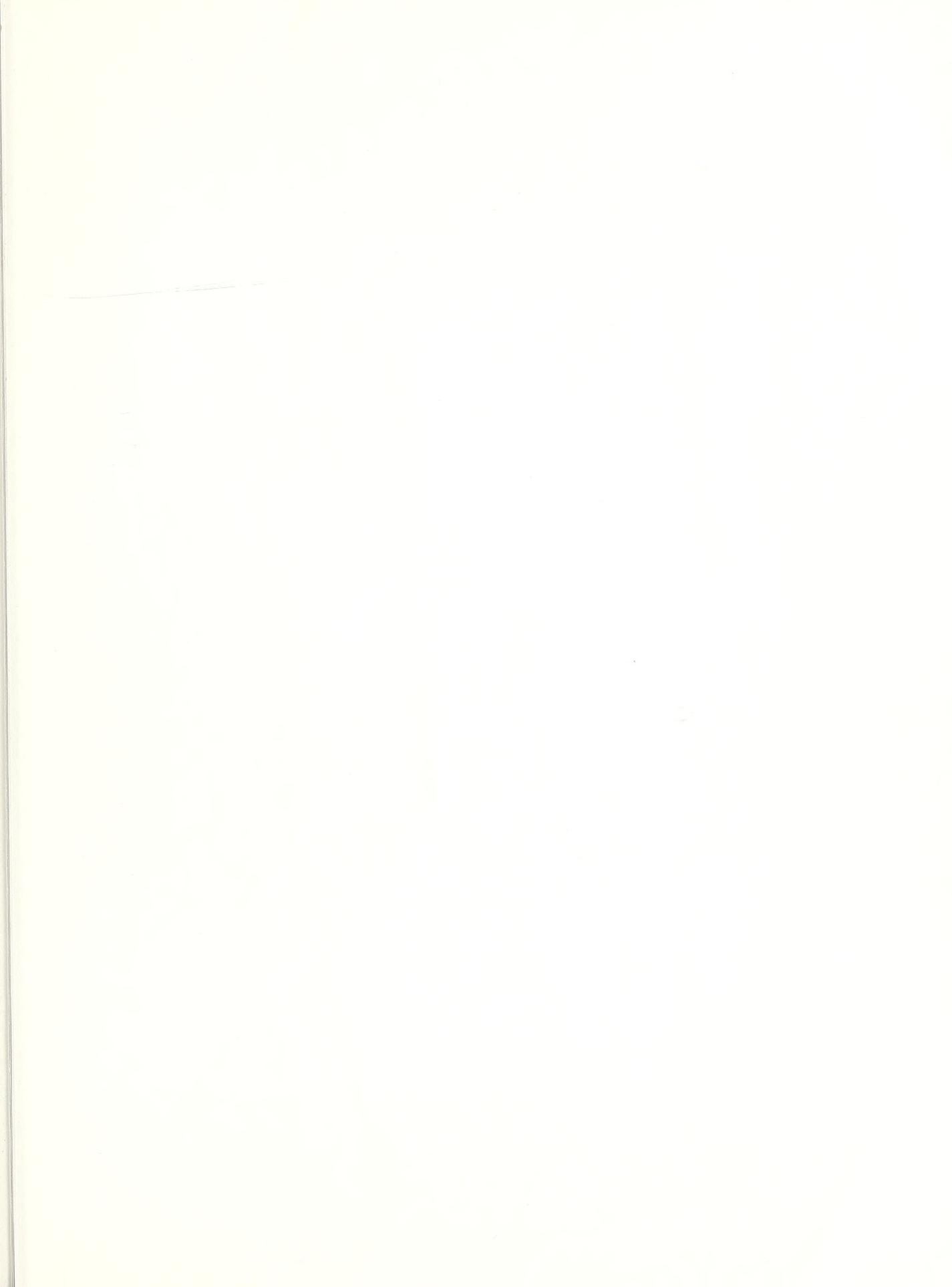
is necessary to determine the fate of nonpoint source pollutants originating from agricultural watersheds.

7. We should continue to test distributed-runoff and sediment-production models with the existing data and concentrate on adapting models for use on larger watersheds. There is also a need for simple empirical, lumped-parameter models for runoff and sediment.
8. Hydrologic records were obtained on the Spring Creek subdivided watershed to improve methods of routing flow and sediment from small areas of a large watershed. Analysis of these records would also provide an estimate of channel loss for various sizes of storms and antecedent conditions.
9. There is a need for improved hydrologic models that account for water in farm ponds and floodwater-retarding impoundments. Pond and reservoir storage records from Spring Creek

could be used for model development and validation.

10. The data collected from the various research studies should be combined to provide data sets for testing hydrologic sediment- and chemical-transport models on a basin scale. The data sets developed in the hydrologic modeling studies should be expanded so that a more complete study of the effects of pollution from agriculture on basins can be determined for downstream areas.
11. The effects of runoff-water quality on receiving waters have not been adequately determined. There are unknown losses and transformations of nutrients and agricultural chemicals during transport. The availability of nutrients carried on sediment and in sediment deposits should be determined for a better assessment of their effects on aquatic ecosystems.





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